Is Nature Supersymmetric?

Beate Heinemann, University of Liverpool

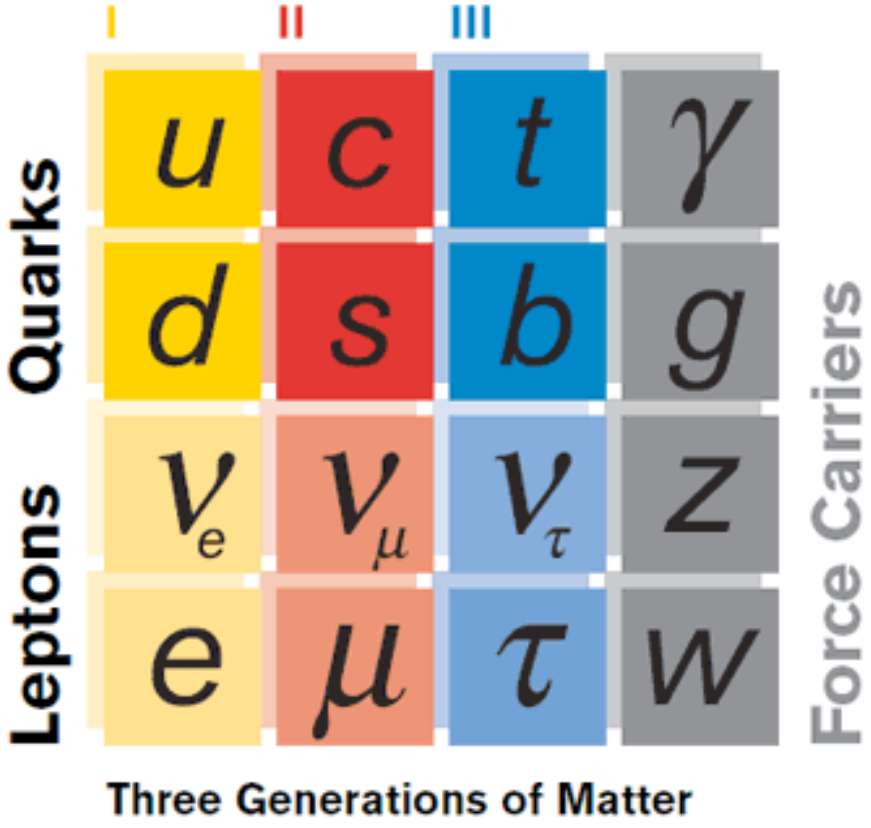
- Introduction
- High Energy Colliders
  - Tevatron and LHC
- Searches
  - Gluinos and squarks
  - Charginos and Neutralinos
  - Indirect Searches
- Summary and Outlook

THE ROYAL SOCIETY

APS Meeting, Dallas, April 2006

The Standard Model

- Matter is made out of fermions:
  - quarks and leptons
  - 3 generations
- Forces are carried by Bosons:
  - Electroweak: γ,W,Z
  - Strong: gluons
- Higgs boson:
  - Gives mass to particles
  - Not found yet => see next talk by T. Junk



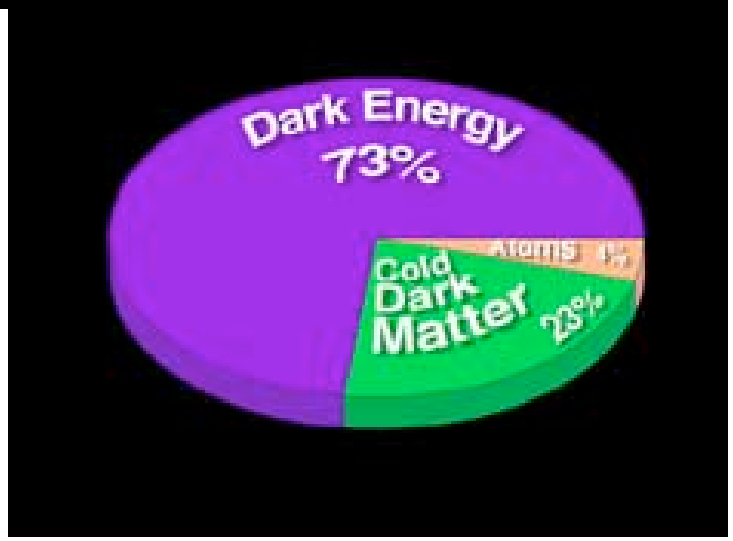
Does the Standard Model work?

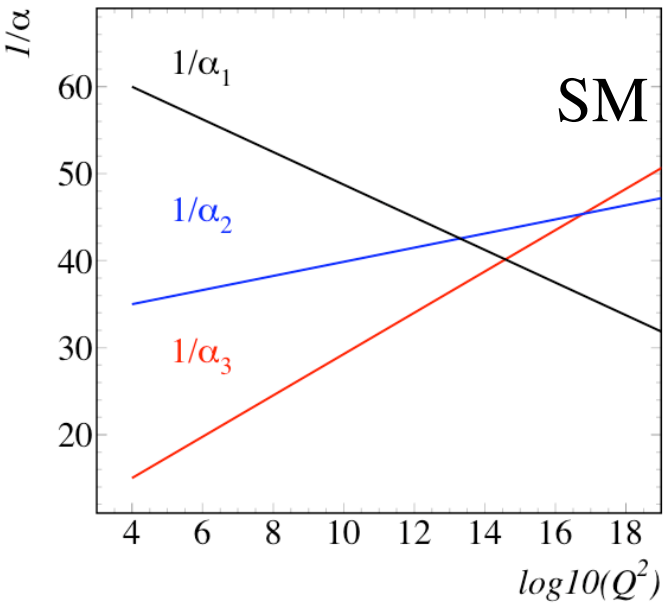
pro's:

- Is consistent with electroweak precision data

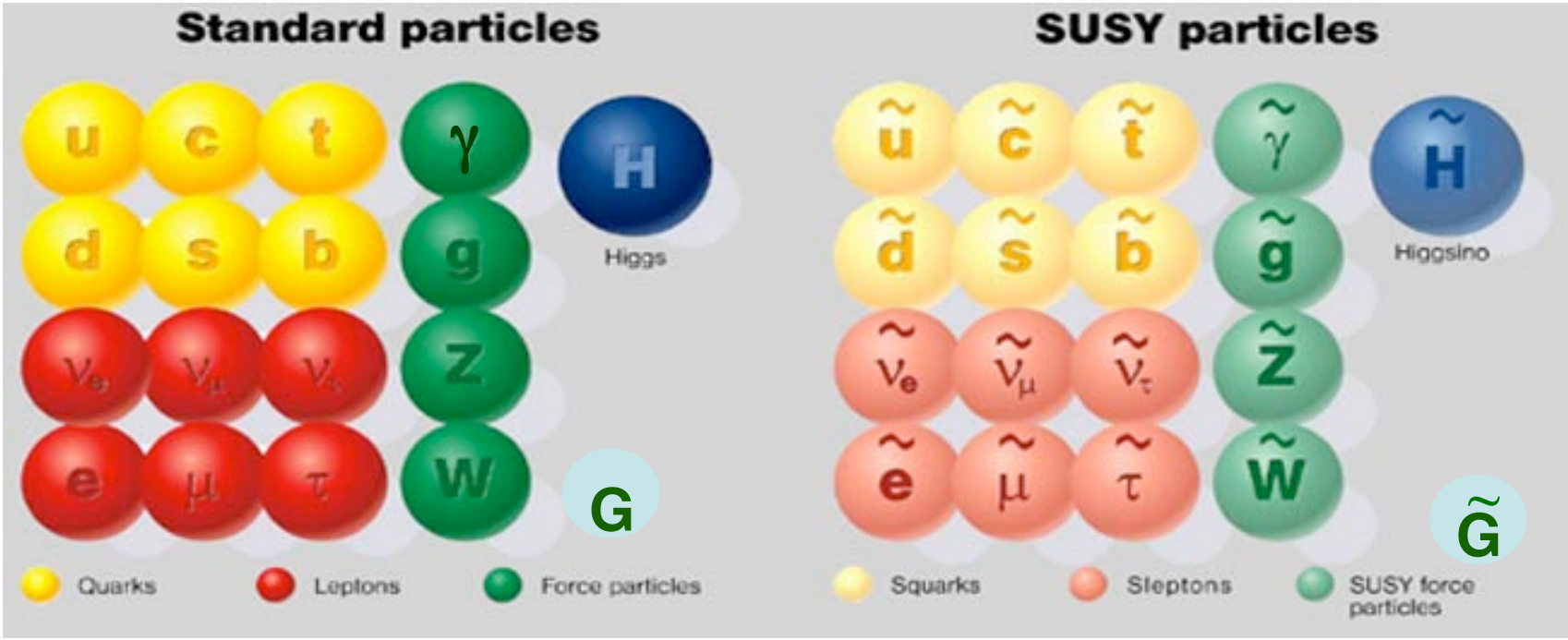
con's:

- Accounts for only 4% of energy in Universe
- Lacks explanation of mass hierarchy in fermion sector
- does not allow grand unification of forces
- Requires fine-tuning (large radiative corrections in Higgs sector)
- Where did all the antimatter go?
- Why do fermions make up matter and bosons carry forces?





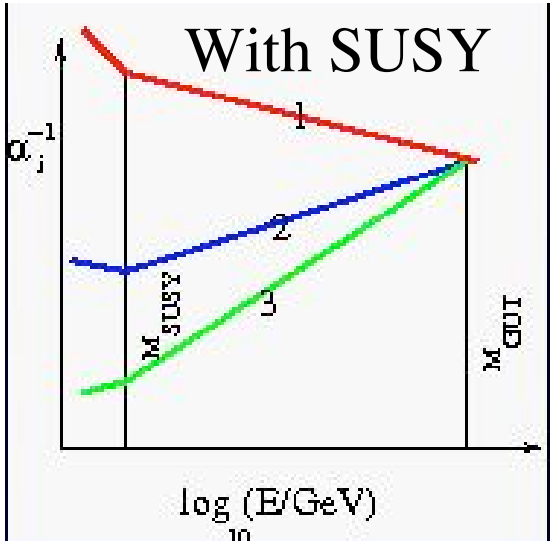
Supersymmetry (SUSY)

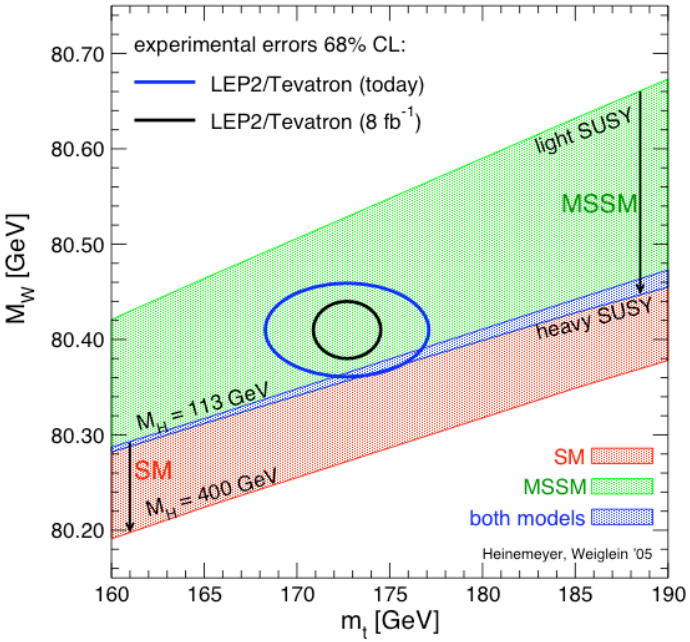


- SM particles have supersymmetric partners:
  - Differ by 1/2 unit in spin
    - Sfermions (squarks, selectron, smuon, …): spin 0
    - gauginos (chargino, neutralino, gluino,…): spin 1/2
- No SUSY particles found as yet:
  - SUSY must be broken: breaking mechanism determines phenomenology
  - More than 100 parameters even in "minimal" models!

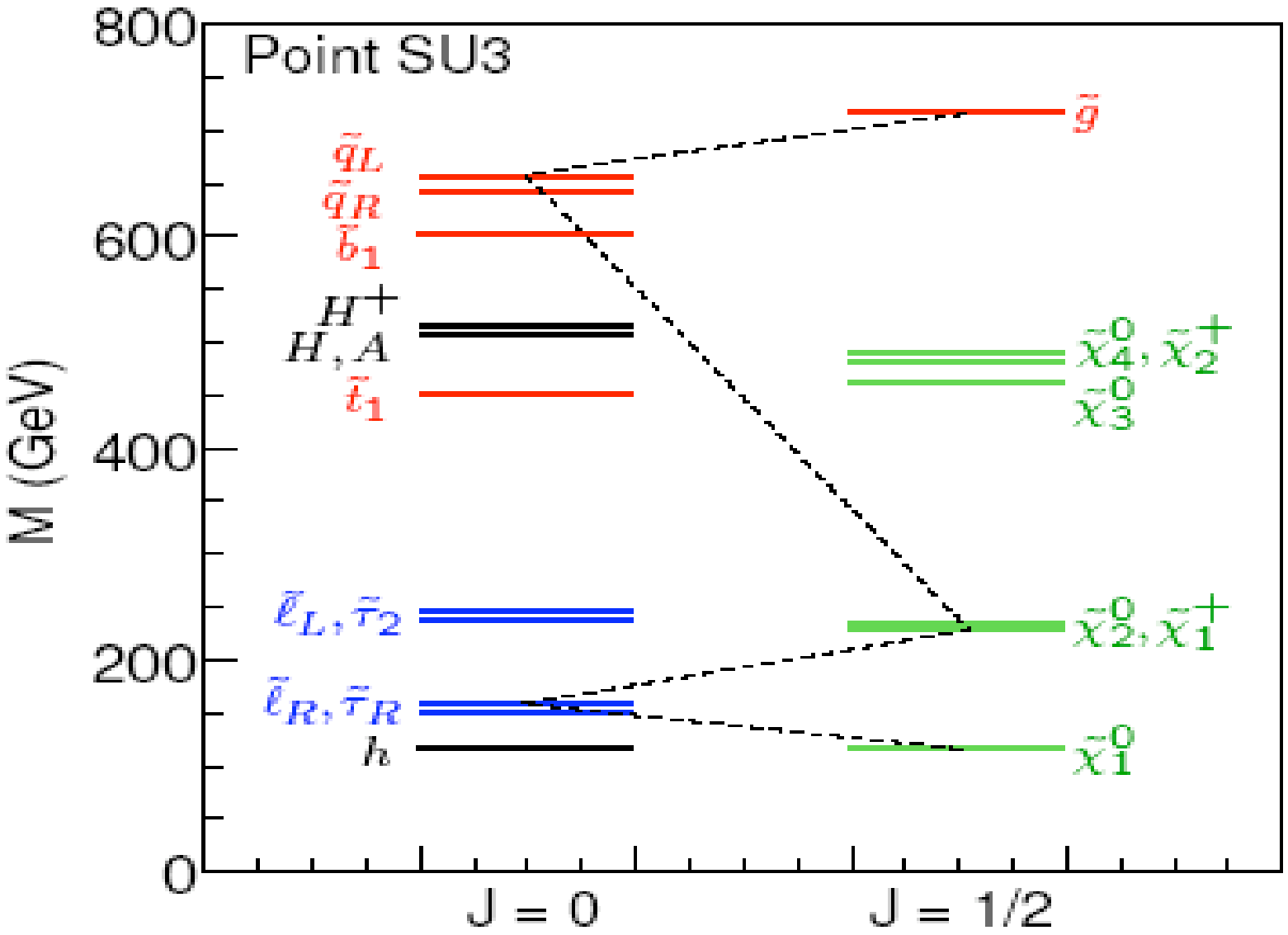
What's Nice about SUSY?

- Introduces symmetry between bosons and fermions
- Unifications of forces possible
- Dark matter candidate exists:
  - The lightest neutral gaugino
  - Consistent with cosmology data
- No fine-tuning required
  - Radiative corrections to Higgs acquire SUSY corrections
    - Cancellation of fermion and sfermion loops
- Also consistent with precision measurements of M_W and M_{top}
  - But may change relationship between M_W, M_{top} and M_H



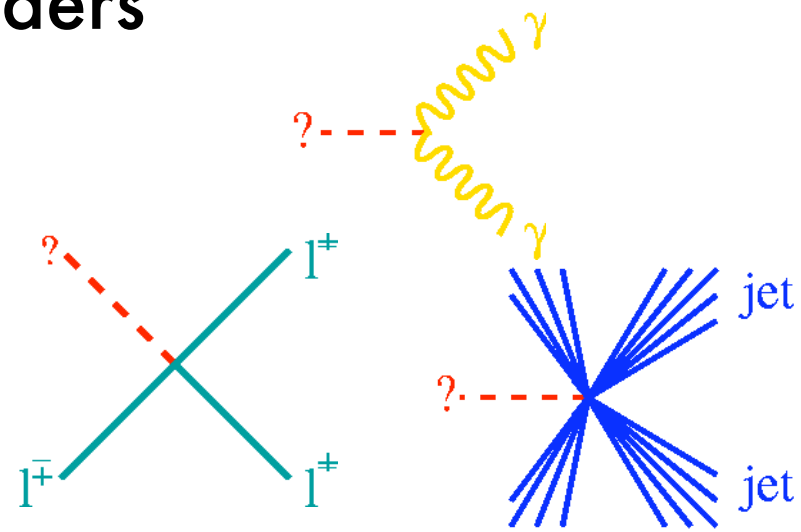


Sparticle Spectrum



SUSY Comes in Many Flavors

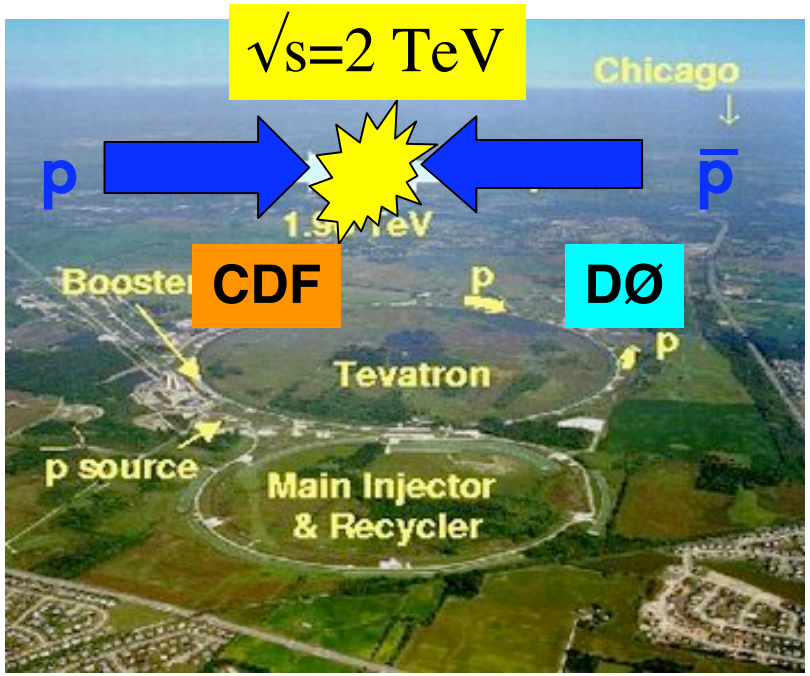
- Breaking mechanism determines phenomenology and search strategy at colliders
  - GMSB:
    - Gravitino is the LSP
    - Photon final states likely
  - mSUGRA
    - Neutralino is the LSP
    - Many different final states
  - AMSB
  - Split-SUSY: sfermions very heavy



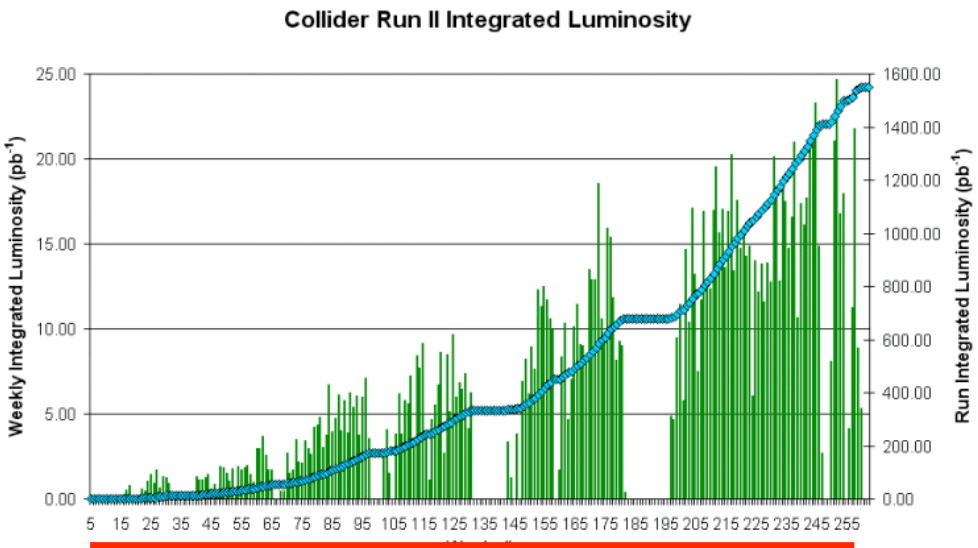
- R-parity
  - Conserved: Sparticles produced in pairs
    - natural dark matter candidate
  - Not conserved: Sparticles can be produced singly
    - constrained by proton decay if violation in quark sector
    - Could explain neutrino oscillations if violation in lepton sector

Where to find SUSY?

Now: Tevatron (<2009)



∫Ldt=1.6 fb^{-1} delivered

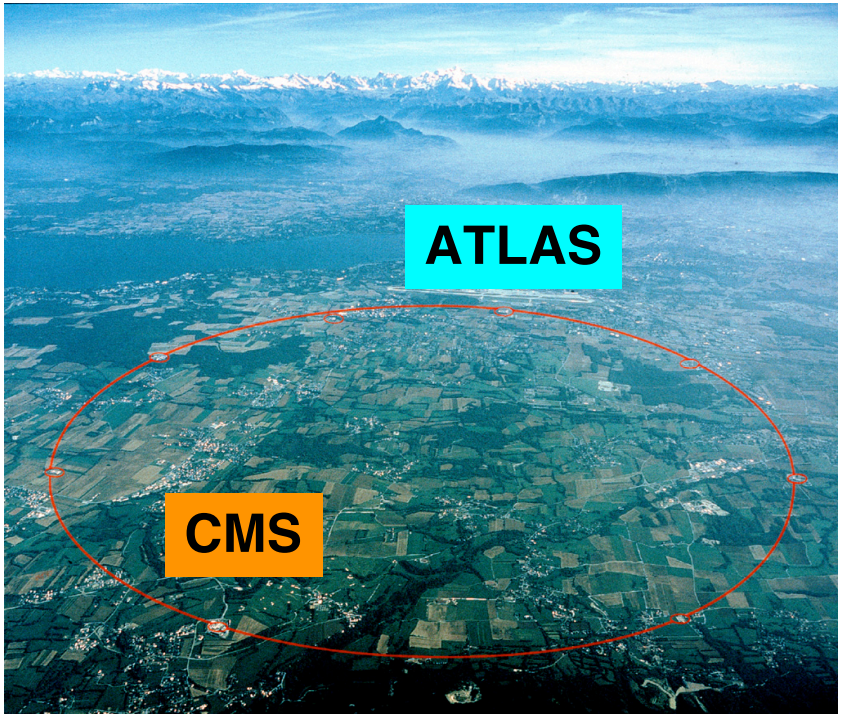


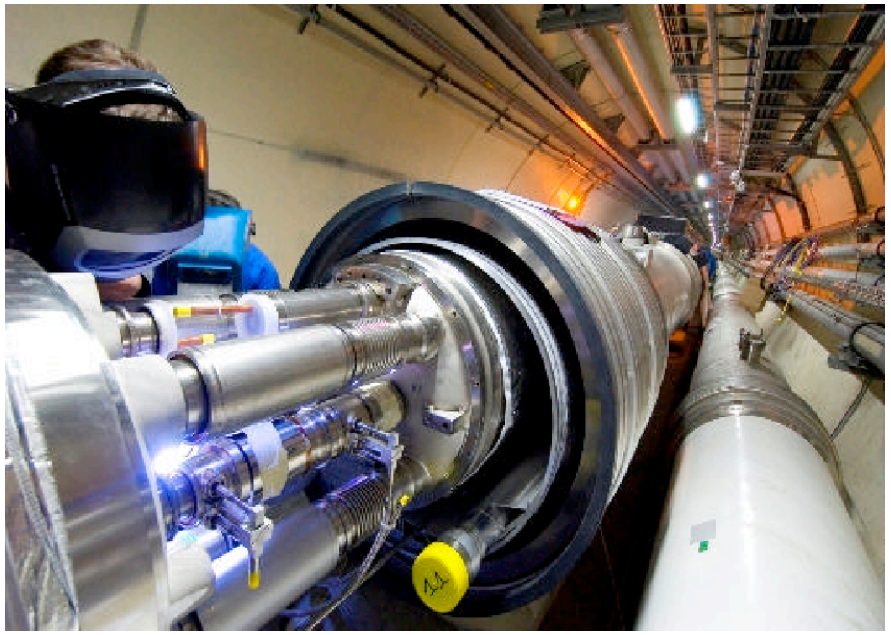
Key parameter: $N=\sigma \bullet \int Ldt$

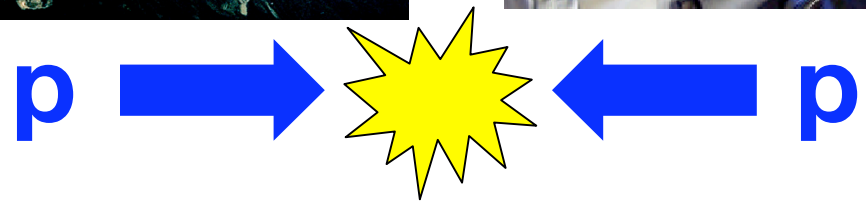
- Tevatron proton-antiproton collider at $\sqrt{s}$=2 TeV:
  - 1 fb^{-1} of data taken, 7 fb^{-1} more to come
- CDF and DØ experiments operating well
  - Data taking efficiency about 85%

Where to find SUSY?

LHC (2007-?)



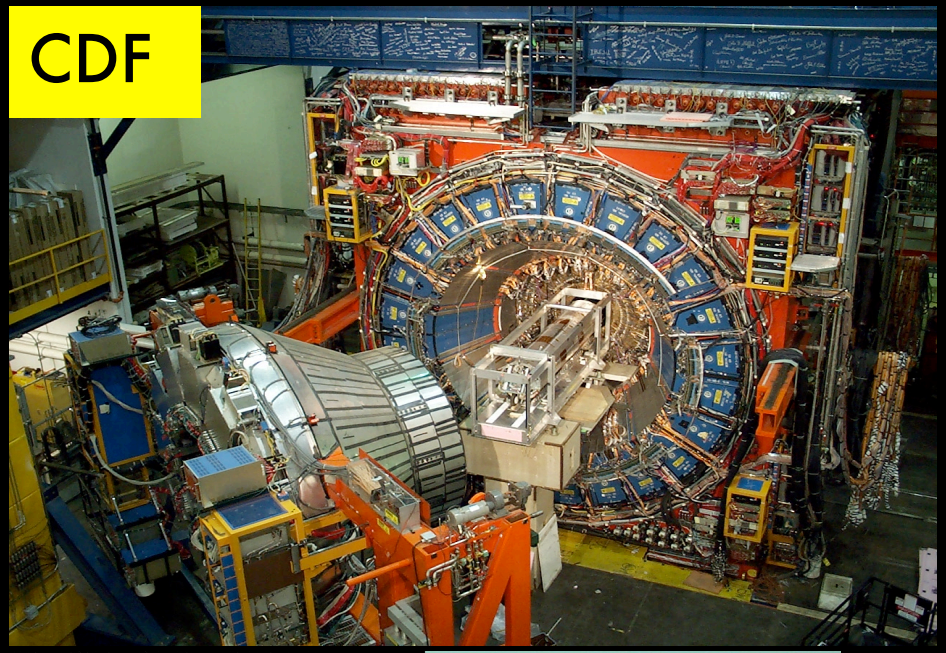




$\sqrt{s}$=14 TeV

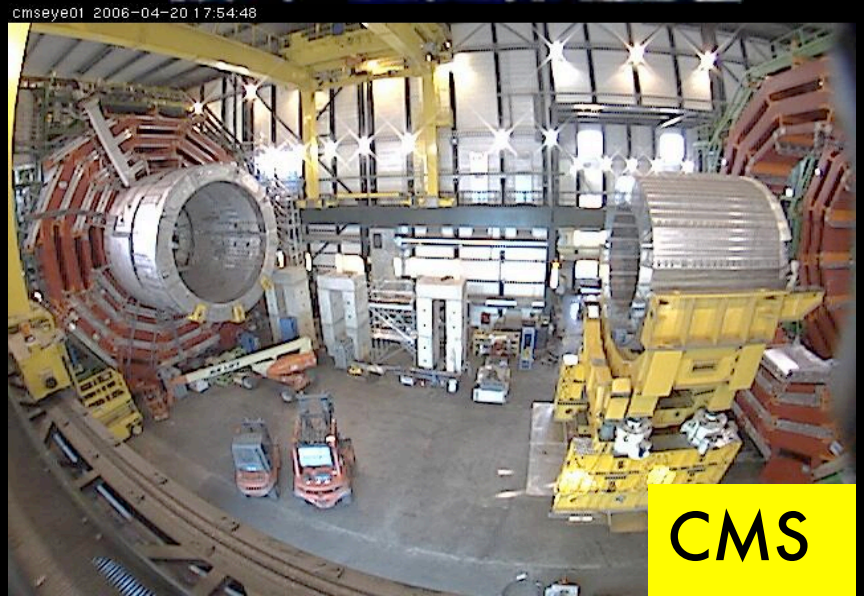
The Detectors

CDF



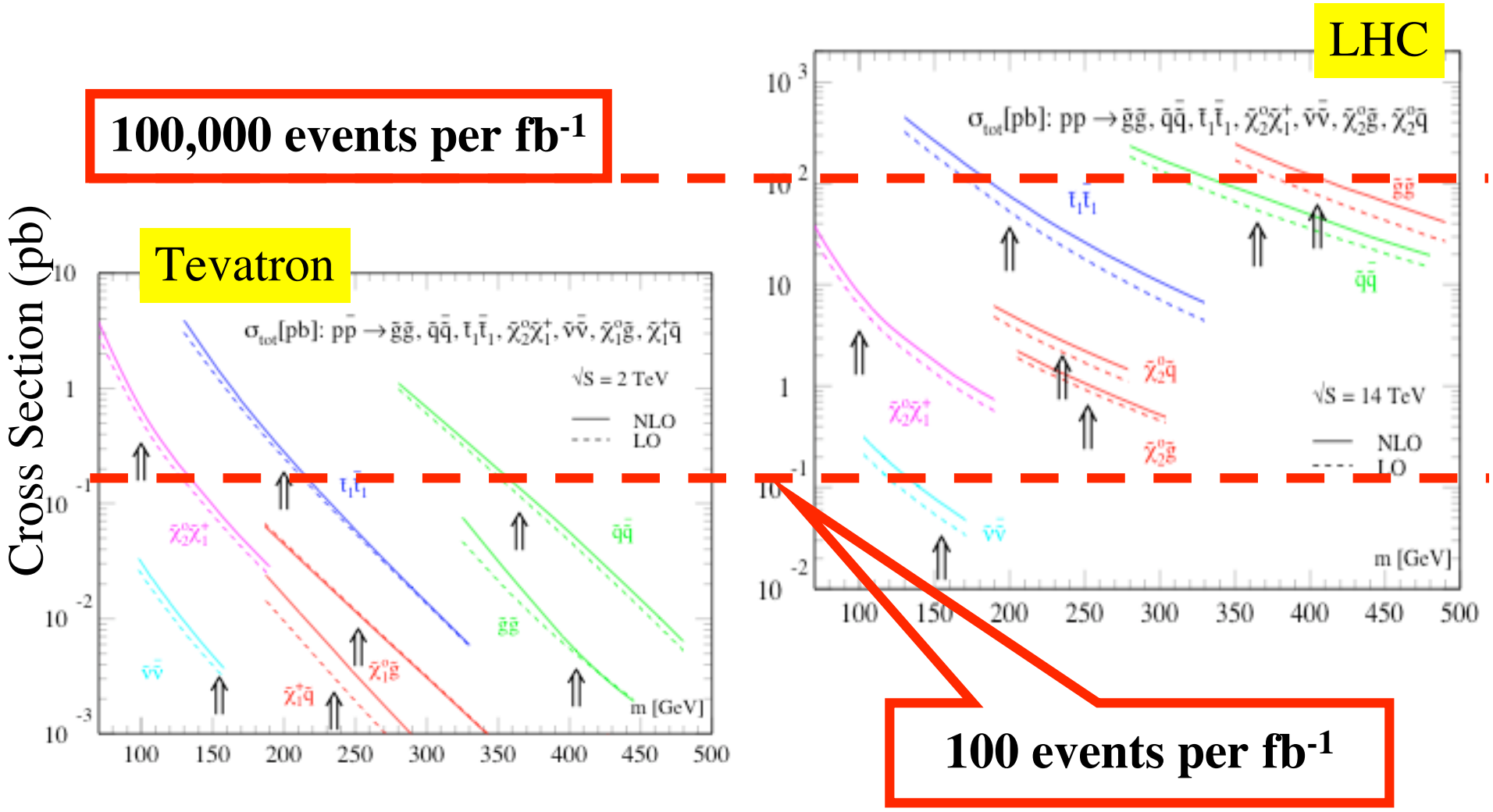
DØ

ATLAS



CMS

Sparticle Cross Sections

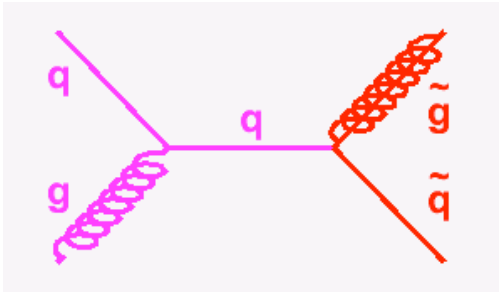


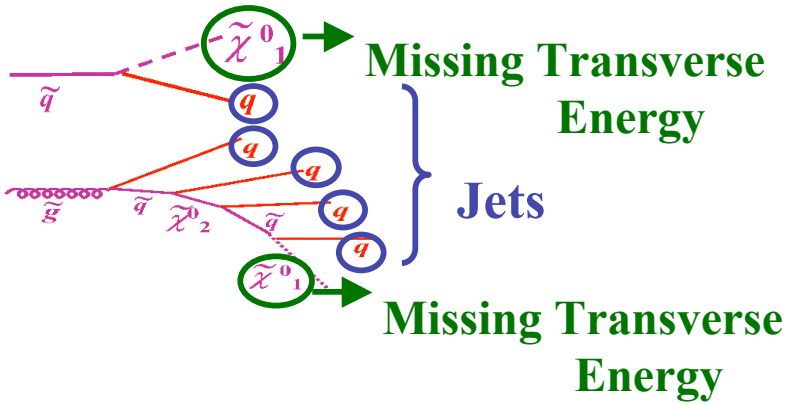
T. Plehn, PROSPINO

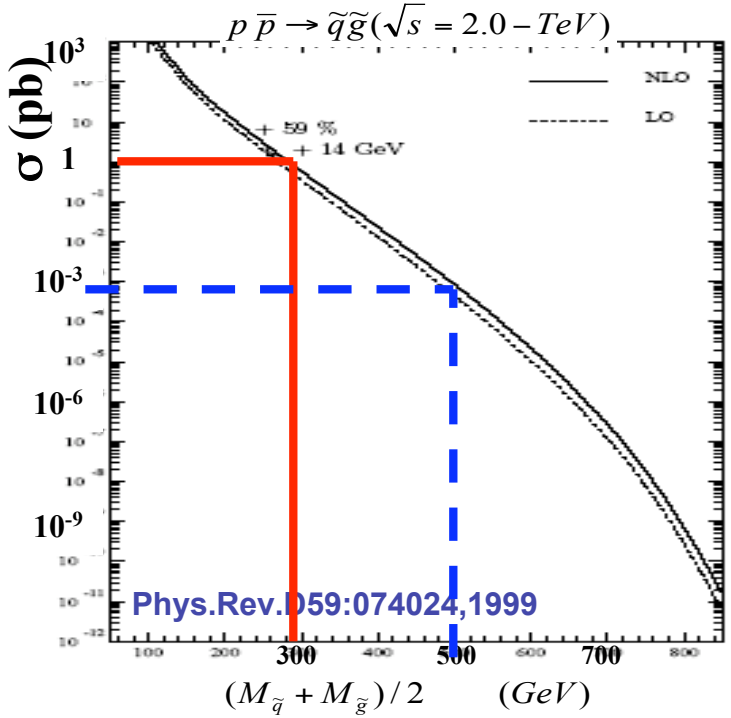
Squarks and Gluinos

Generic Squarks and Gluinos

- Squark and Gluino production:
  - Signature: jets and $\not{E}_t$

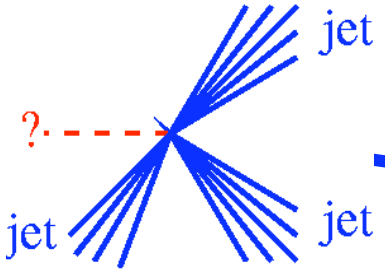


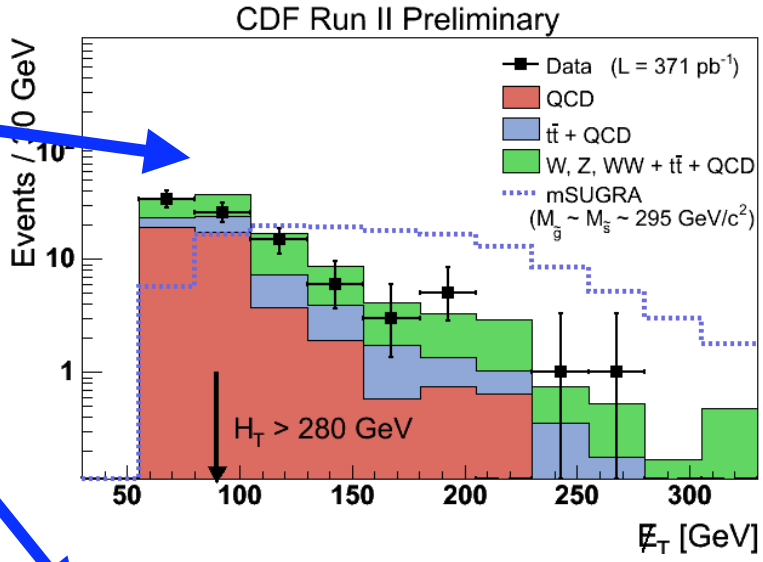


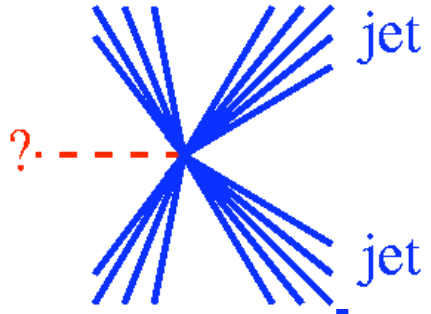


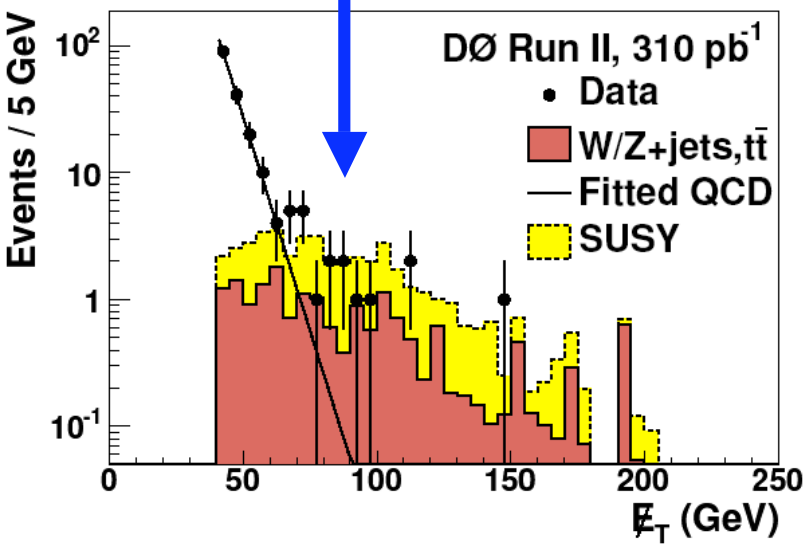
- Strong interaction => large production cross section
  - for $M(\tilde{g}) \approx 300$ GeV/c^2:
    - 1000 event produced
  - for $M(\tilde{g}) \approx 500$ GeV/c^2:
    - 1 event produced

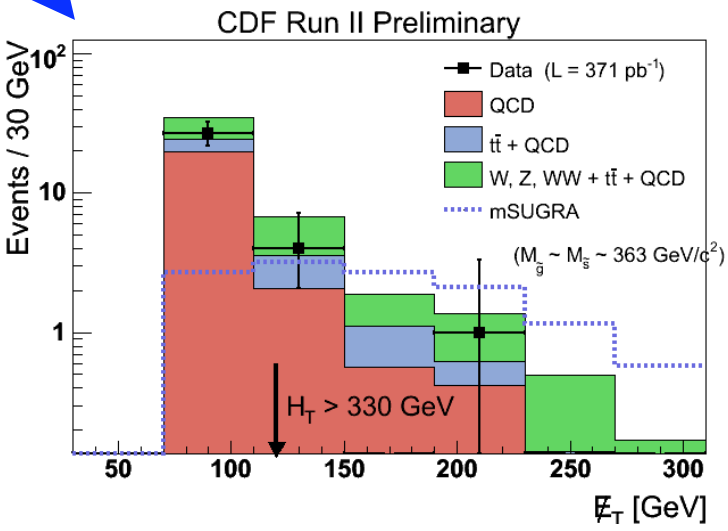
Missing E_T Distributions





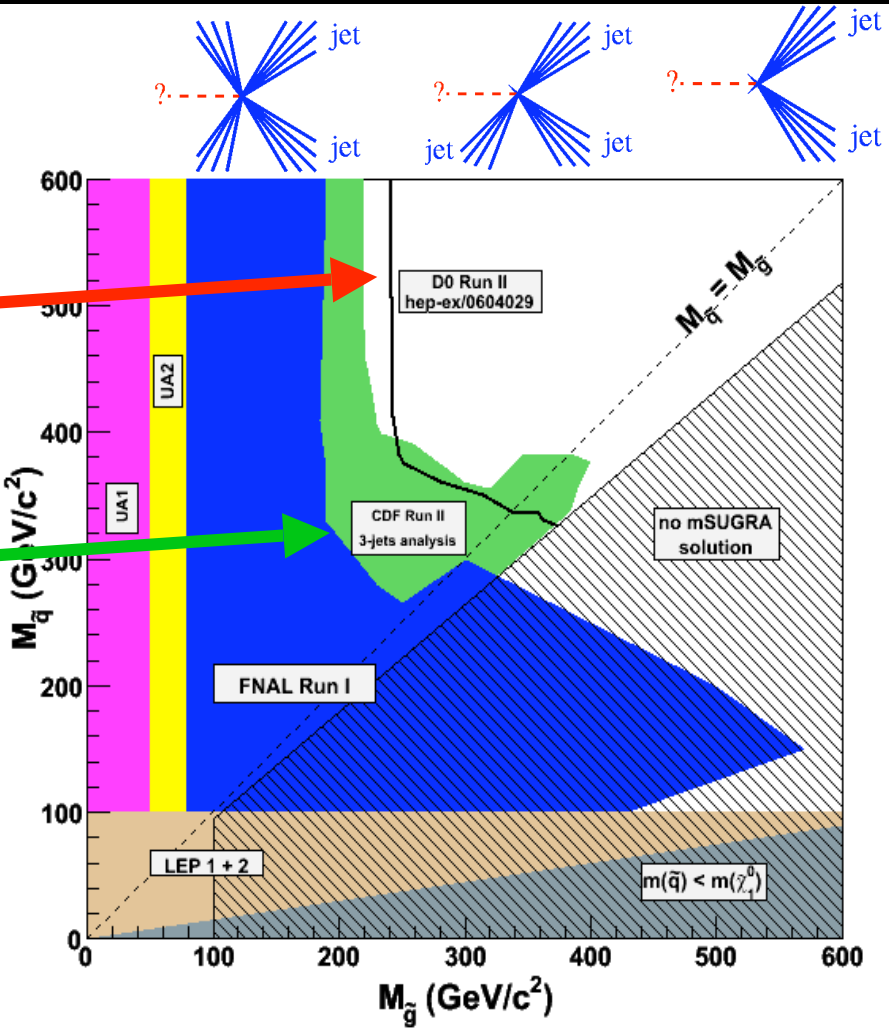




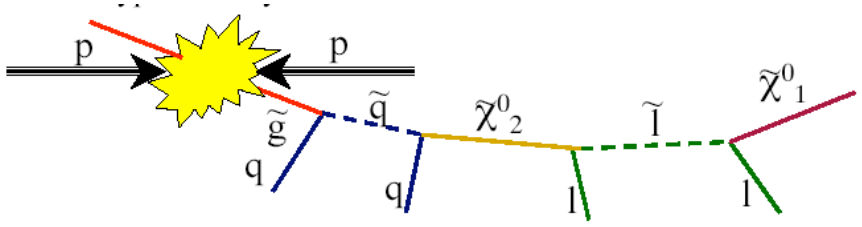


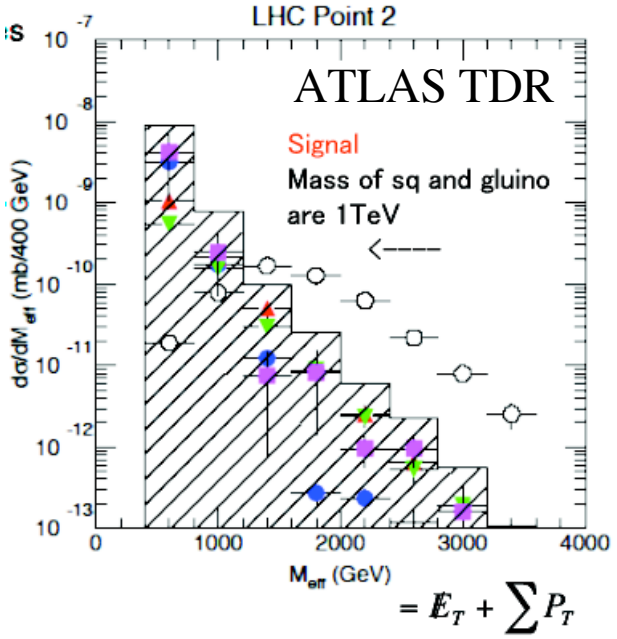
Squark and Gluino Mass Limits

- No evidence for excess of events:
  - DØ excluded gluinos up to 230 GeV independent of squark mass:
    - Mostly due to 4-jet analysis
  - CDF reaches 400 GeV exclusion for m($\tilde{q}$)≈m($\tilde{g}$)
    - Statistical downward fluctuation
    - Optimised for this region
- Stop and sbottom quarks are excluded/negligible in analyses

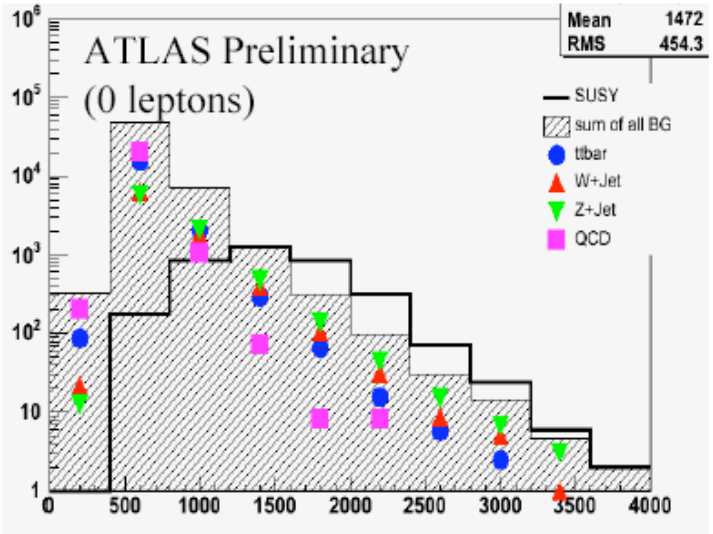


Squarks/Gluinos at the LHC

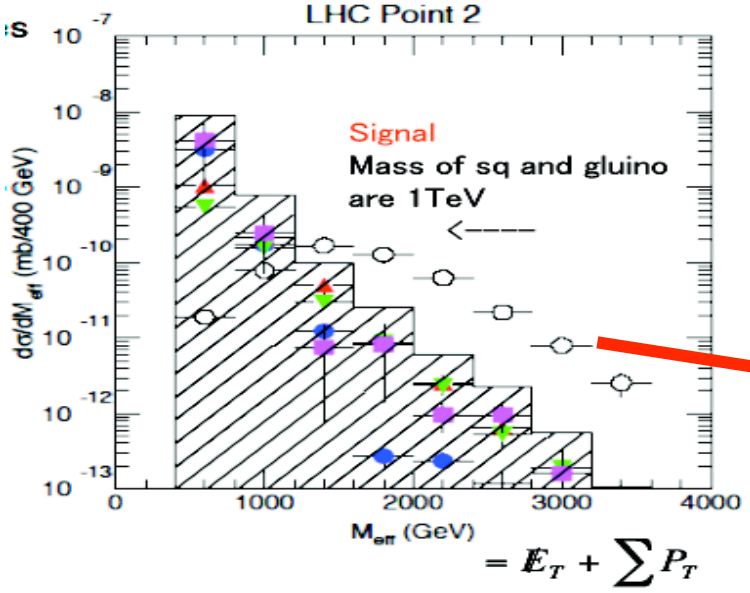


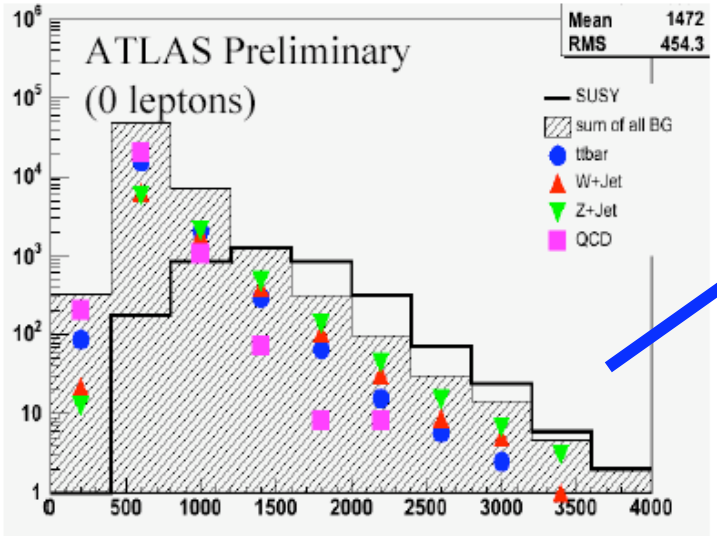


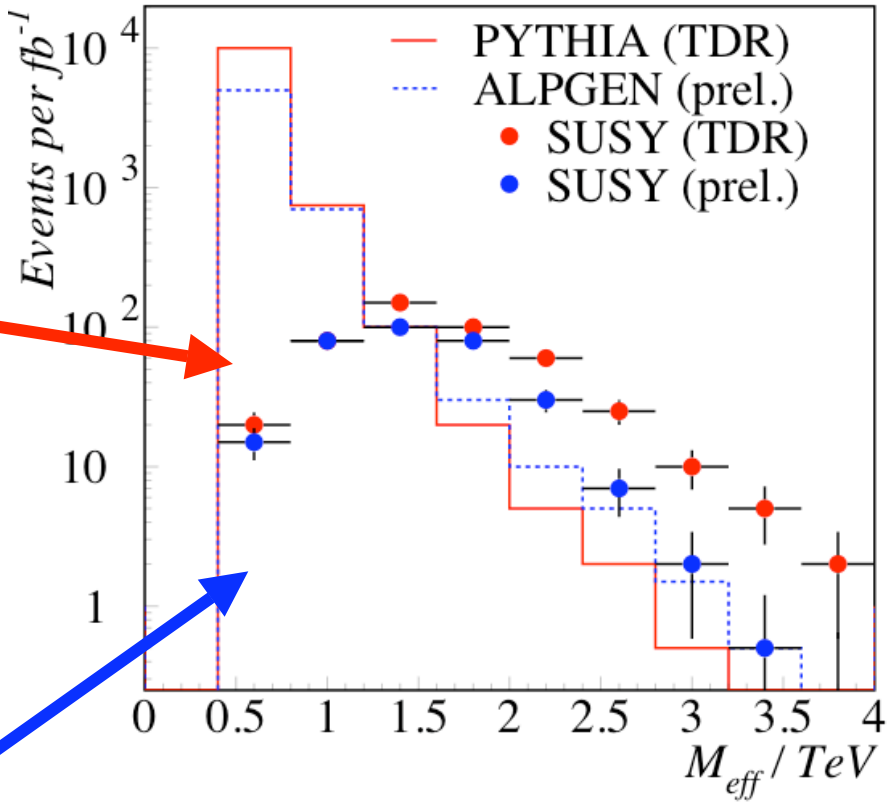
- Squark/Gluino cross sections 1000 times larger than at Tevatron!
  - Missing E_T + jets excellent discovery signature
  - Long decay chains
    - lepton signatures also very promising
- Discussion on PYTHIA validity:
  - Does PYTHIA represent data well enough?
  - Is ALPGEN more realistic?
  - Is discovery potential compromised?



Direct Comparison



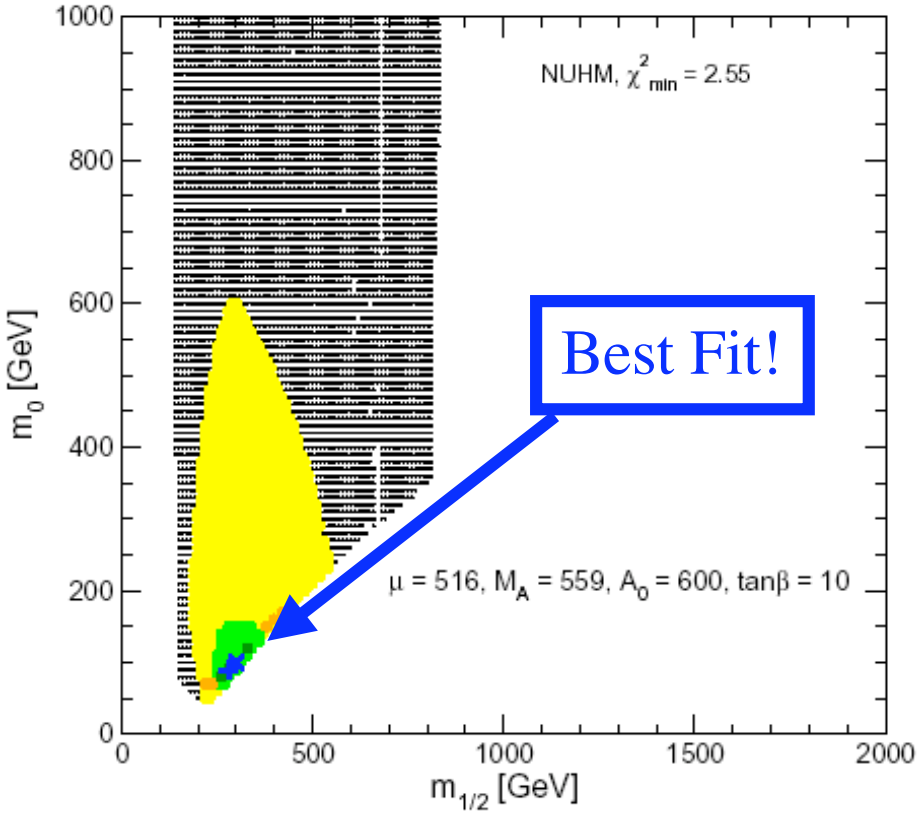


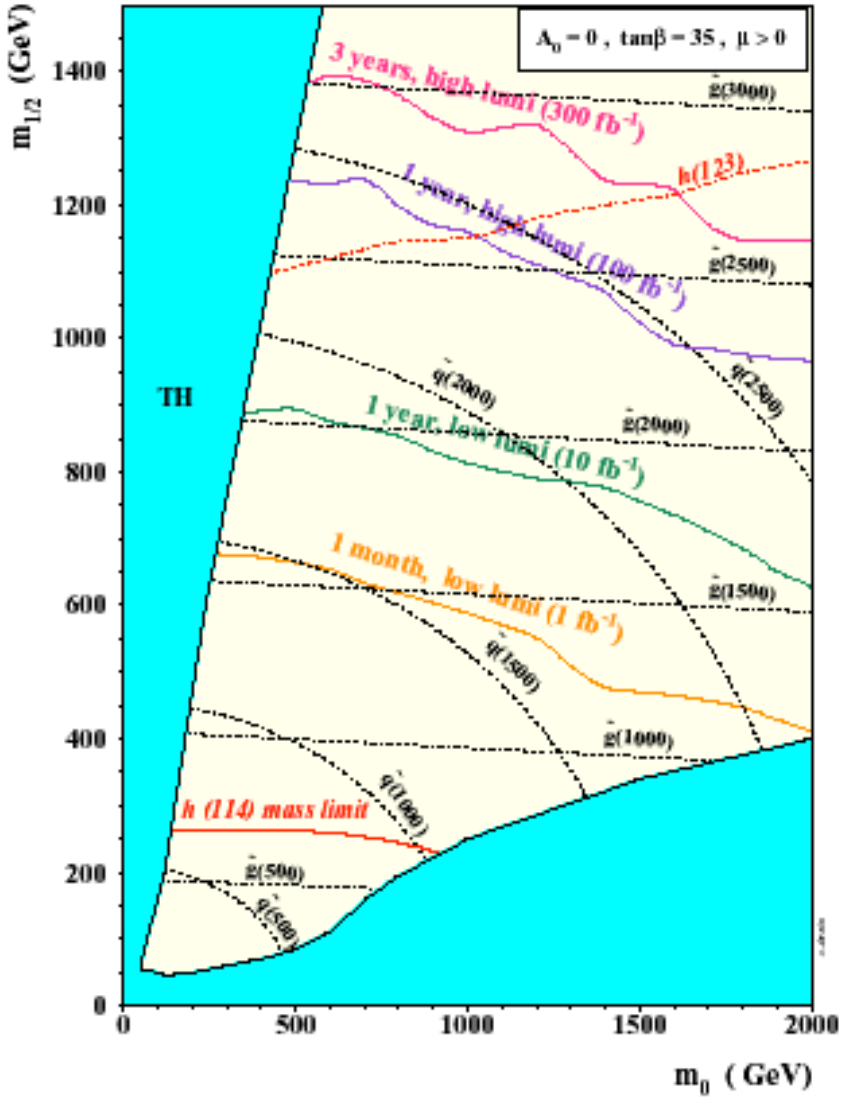


Signal changed a lot more than the background!!! (noticed by I. Hinchliffe)

Squarks/Gluinos at the LHC

- Excellent potential:
  - Precision data indicate low scale of SUSY
  - Should be found at LHC



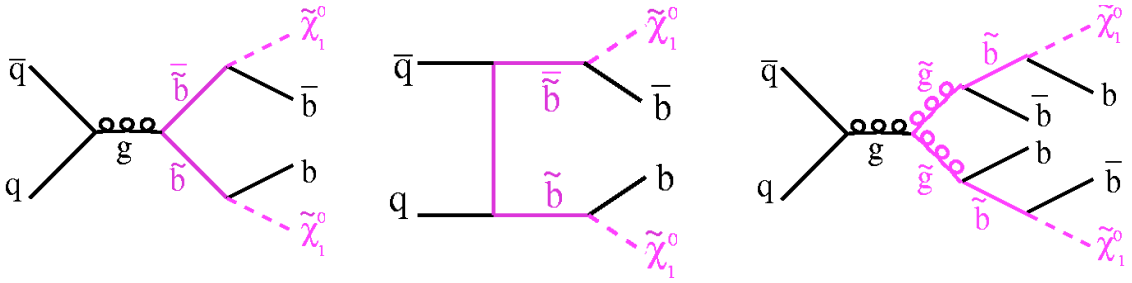


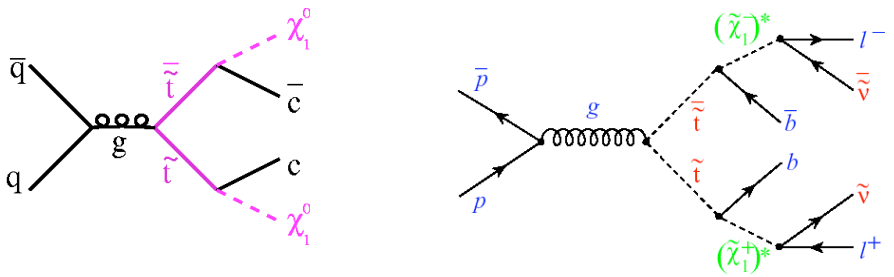
hep-ph/0602220: Ellis, Heinemeyer, Olive, Weiglein

3rd generation Squarks

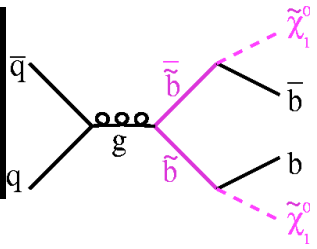
- 3rd generation is special: mass could be much lower

- Direct production or from gluino decays:
  - $pp \rightarrow b\tilde{b}$ or $t\tilde{t}$
  - $pp \rightarrow g\tilde{g} \rightarrow b\tilde{b}b\tilde{b}$ or $t\tilde{t}t\tilde{t}$
- Decay of sbottom and stop:
  - $\tilde{b} \rightarrow b\tilde{\chi}^0$
  - Stop depends on mass:
    - Heavy: $\tilde{t} \rightarrow t\tilde{\chi}^0$
    - Medium: $\tilde{t} \rightarrow b\tilde{\chi}^{\pm} \rightarrow bW\tilde{\chi}^0$
    - Light: $\tilde{t} \rightarrow c\tilde{\chi}^0$

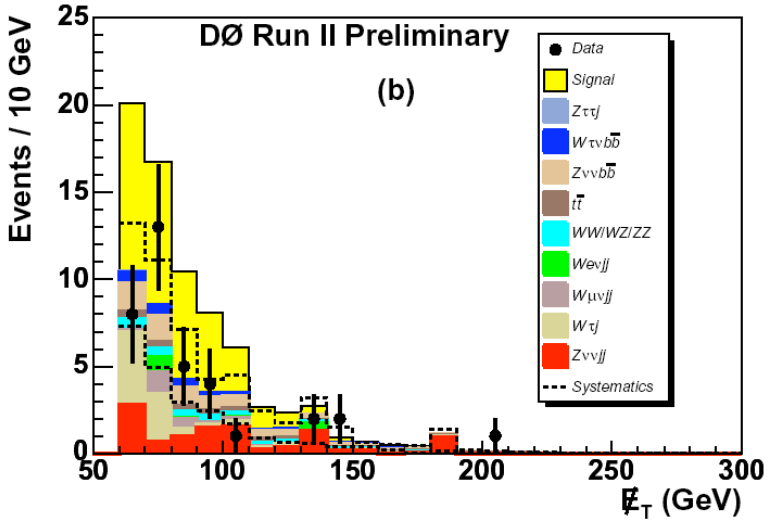


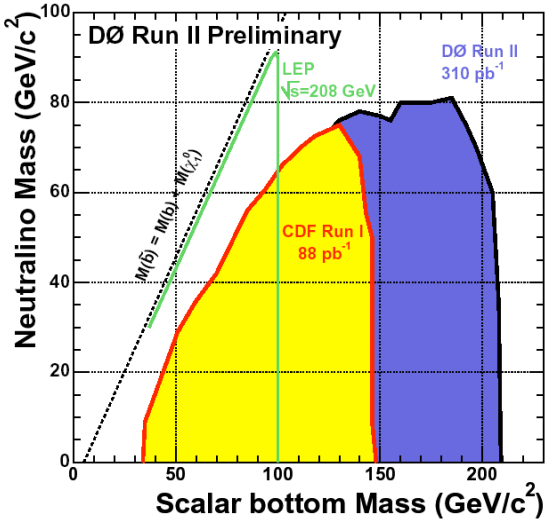


Sbottom Quarks



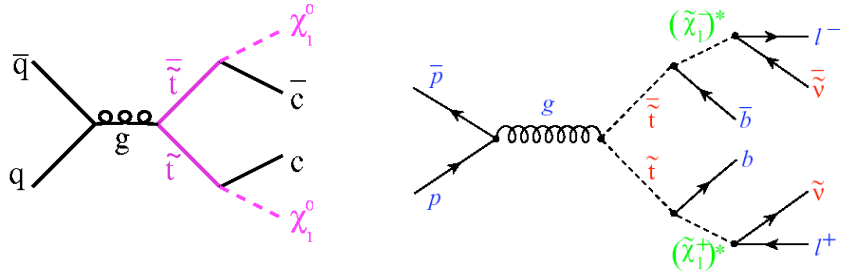
- Selection:
  - Two jets, one b-tagged:
    - E_{T1}>40-70 GeV
    - E_{T2}>15-40 GeV
  - Missing E_T>60-100 GeV
  - Optimisation of cuts for different mass regions
- Result:
  - Data agree well with background
  - Exclude sbottom masses up to 200 GeV
    - Depending on neutralino mass

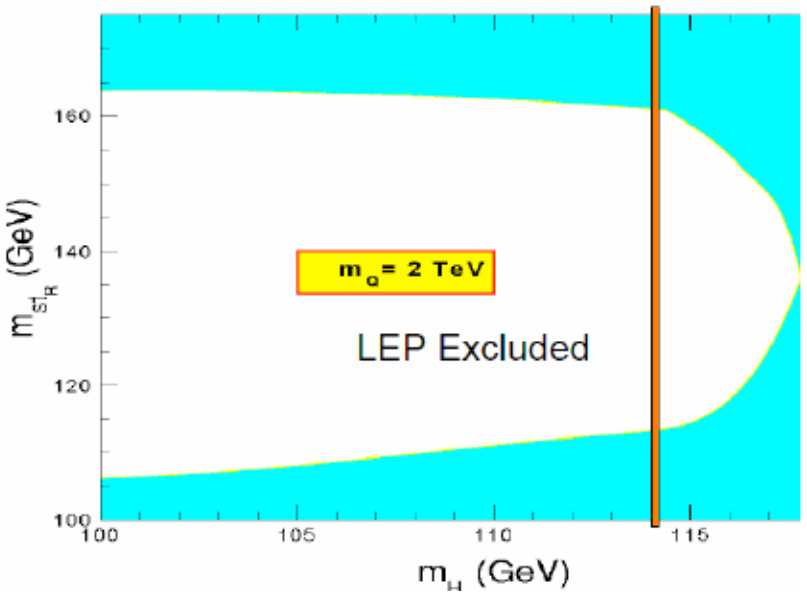




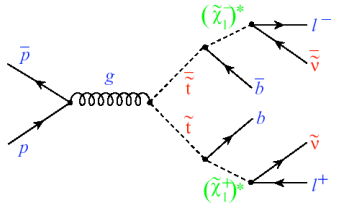
Light Stop–Quark: Motivation

- If stop quark is light:
  - decay via $\tilde{t} \to b l \tilde{\nu}$ or $\tilde{t} \to c \tilde{\chi}_1^0$
- E.g. consistent with baryogenesis:
  - Balazs, Carena, Wagner: hep-ph/0403224
  - $m(\tilde{t})-m(\tilde{\chi}_1^0) \approx 15\text{-}30$ GeV/c^2
  - $m(\tilde{t}) < 165$ GeV/c^2





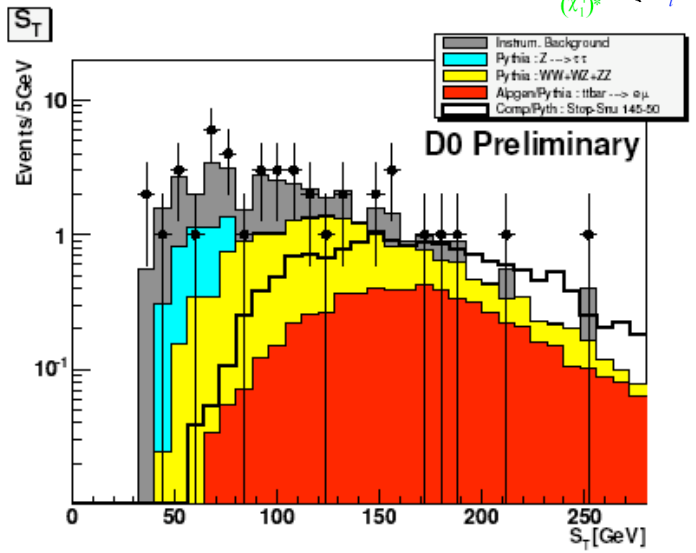
Stop

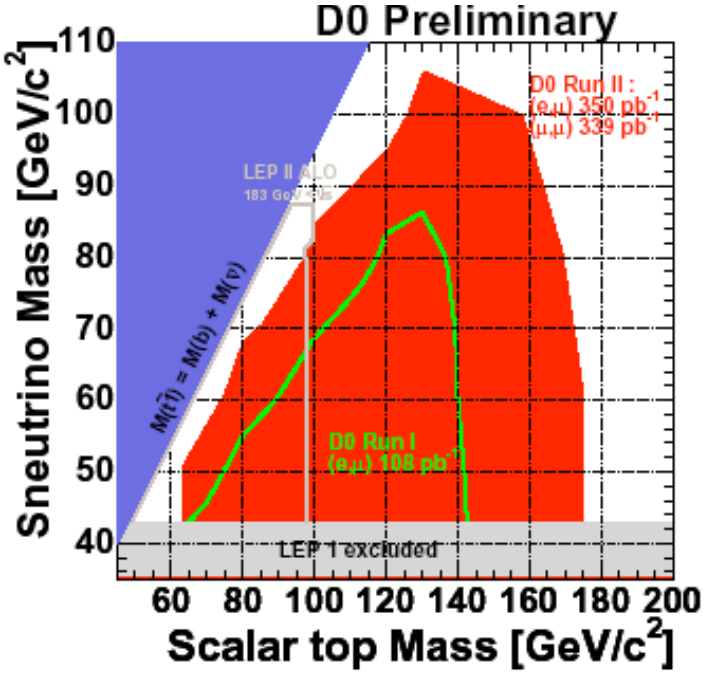


- Selection by DØ
  - 2 leptons: eμ, μμ
  - Missing E_T>15 GeV
  - Topological cuts to suppress background
    - Optimized depending on mass difference of stop and sneutrino
- Results

Cut	SM Bg.	Obs.
A	23.0+-3.1	21
B	34.6+-4.0	34
C	40.7+-4.4	42

Exclude stop masses up to m_{top}

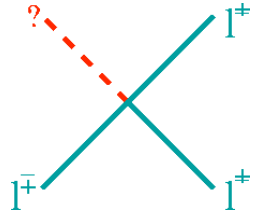


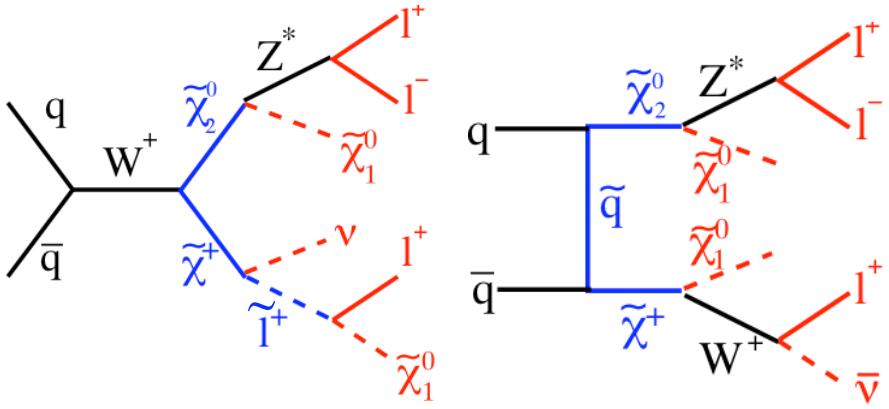


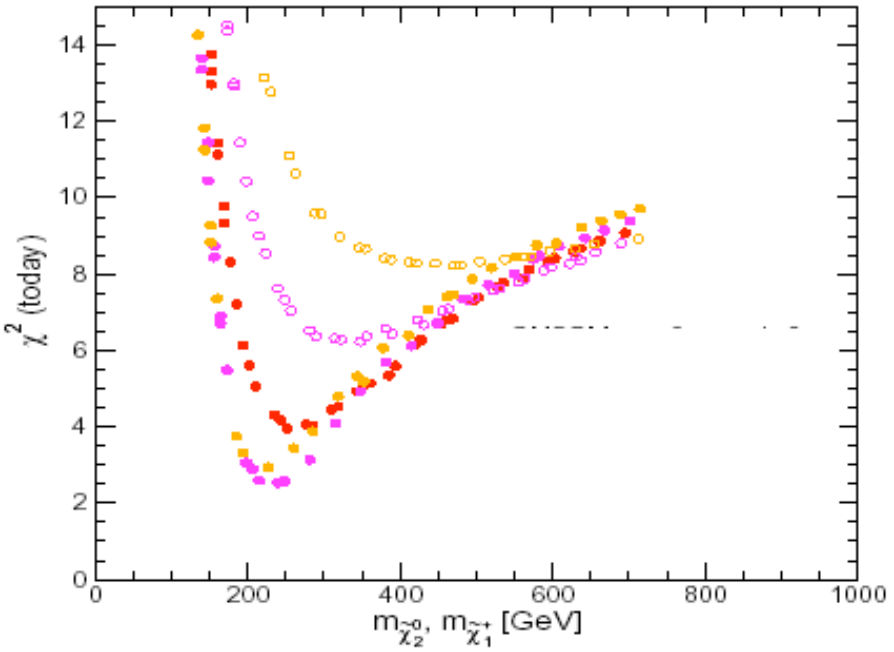
Charginos and Neutralinos

Charginos and Neutralinos

- Charginos and Neutralionos:
  - SUSY partners of W, Z, photon, Higgs
  - Mixed states of those
- Signature:
  - 3 leptons + $\not\!\!E_T$
  - "Golden" signature at Tevatron
- Recent analyses of EWK precision data:
  - J. Ellis, S. Heinemeyer, K. Olive, G. Weiglein:
    - hep-ph/0411216
  - Light SUSY preferred

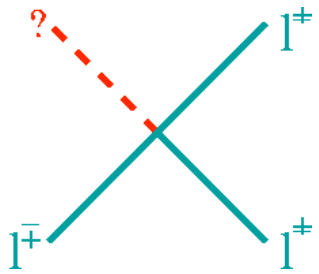


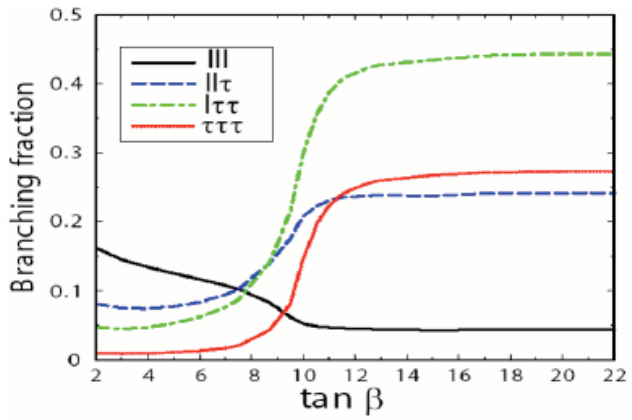




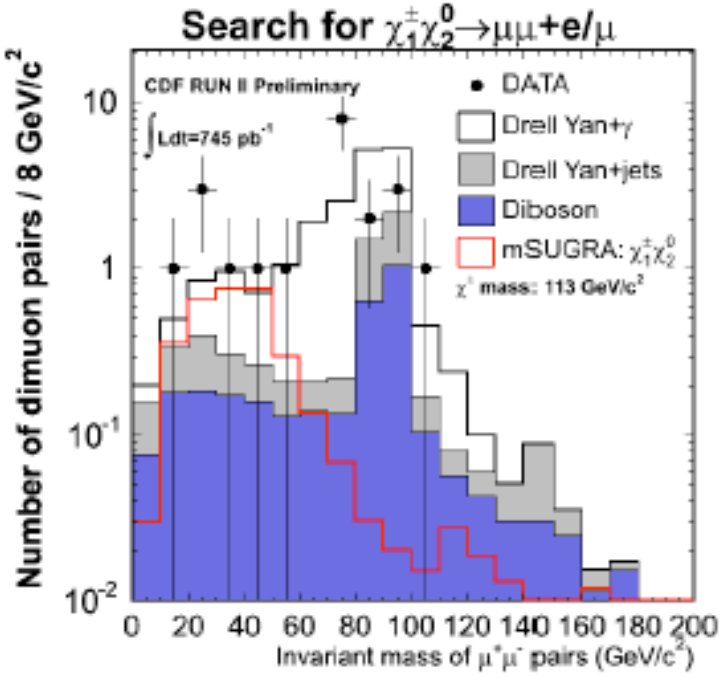
New analyses: 3 leptons + $\not\!\!E_t$

- Many analyses to maximise acceptance:
  - 3 leptons
  - 2 leptons+track
  - 2 leptons with same charge



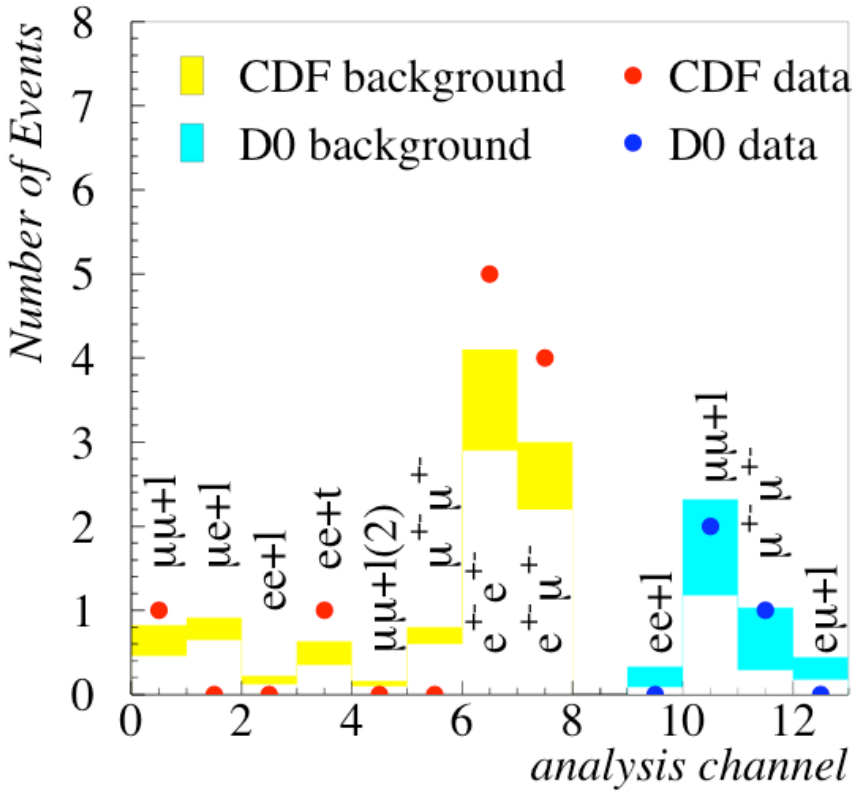


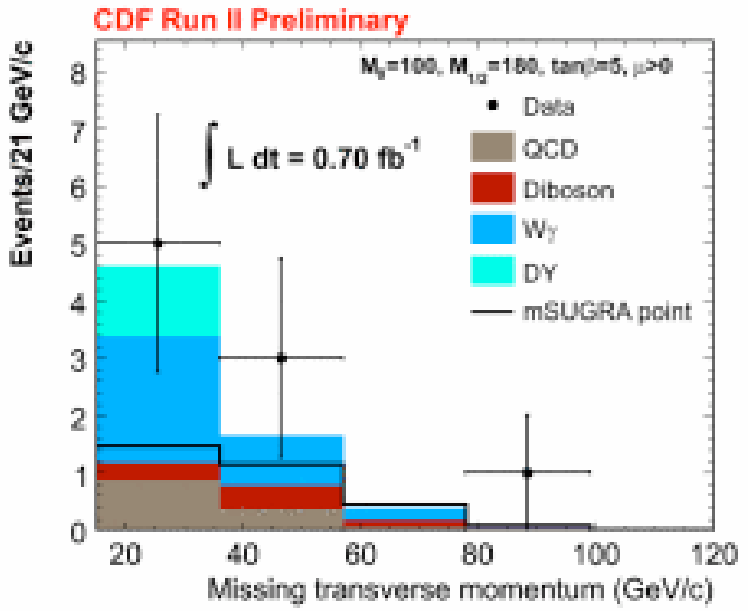
- Other requirements:
  - Dilepton mass >15 GeV and not within Z mass range
    - For same flavor opposite charge leptons
  - Less than 2 jets
  - Significant $\not\!\!E_T$

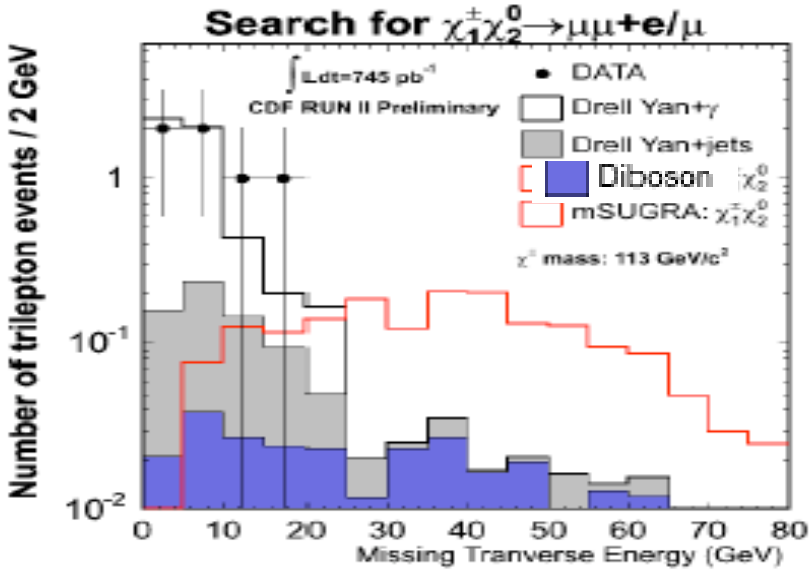


Trileptons: Result

Number of Events

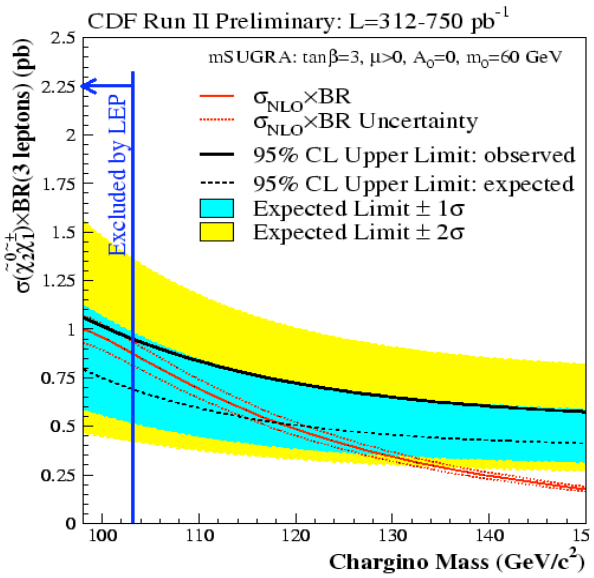


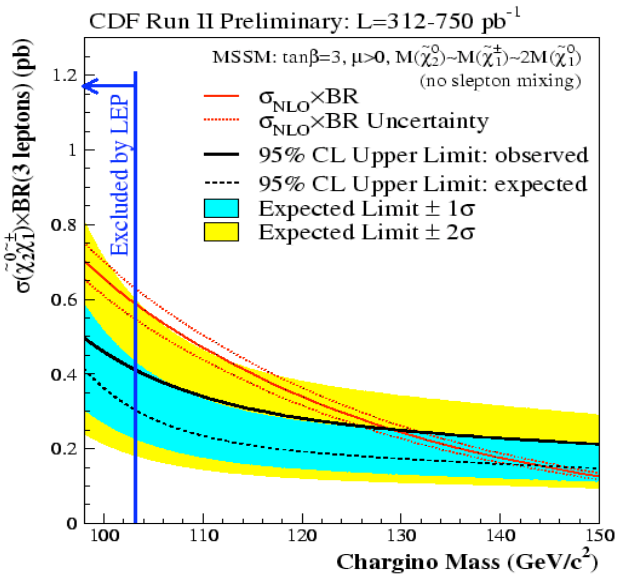




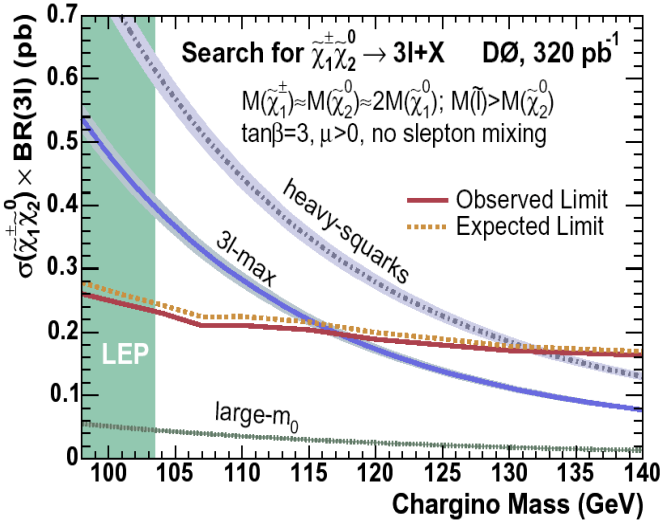
Limits on the Chargino Mass

- Scenario: slepton masses 100-120 GeV => BR to leptons high
- Slepton masses high => No sensitivity yet





PRL 95 151805 (2005)

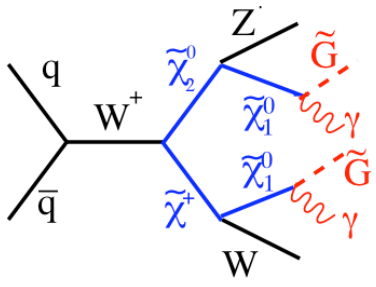


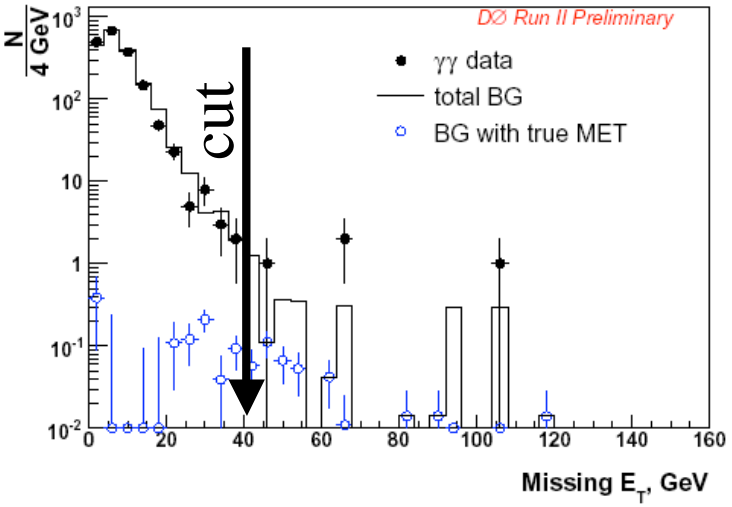
- Slepton mixing (stau dominates):
  - Acceptance worse, no constraint yet
- No slepton mixing:
  - M()>127 GeV (CDF)
  - M()>117 GeV (DØ)

Probe values beyond LEP but very model dependent

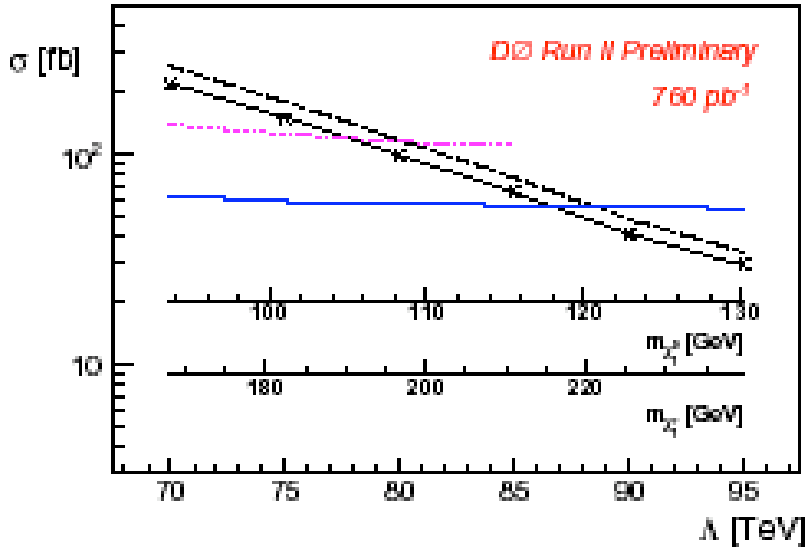
GMSB: $\gamma\gamma+\not{E}_t$

- Assume $\tilde{\chi}^0_1$ is NLSP:
  - Decay to $\tilde{G}+\gamma$
  - $\tilde{G}$ light: m ≈ 1 keV
  - Inspired by CDF ee$\gamma\gamma+\not{E}_t$ event in Run I
    - SM exp.: 10^{-6}
- D0 inclusive search with $\int Ldt$=780 pb^{-1}:
  - 2 photons: E_t > 25 GeV
  - $\not{E}_t$ > 45 GeV





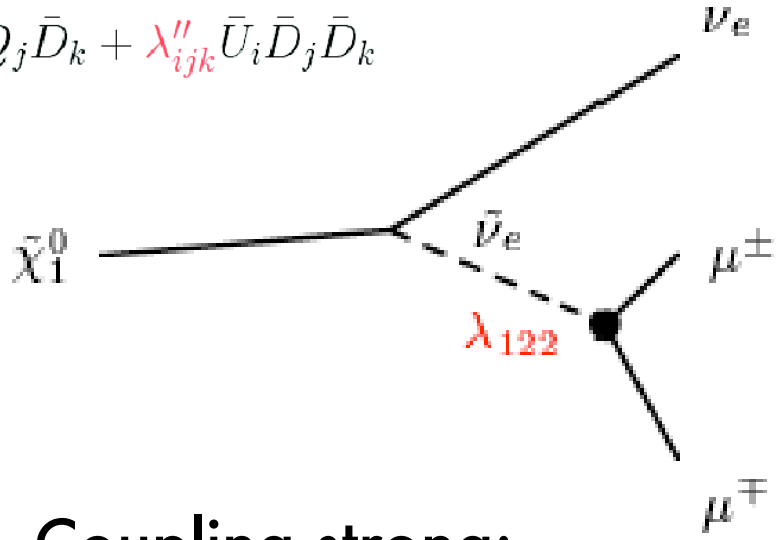
	Exp.	Obs.	m($\tilde{\chi}^+_1$)
DØ	2.1±0.7	4	>220 GeV



CDF result: m(χ^+_1)>168 GeV with 200 pb^{-1}

R-parity violation

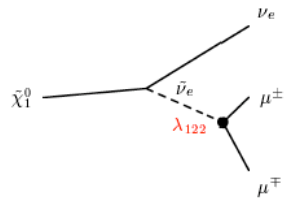
$$W_{\not R_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$



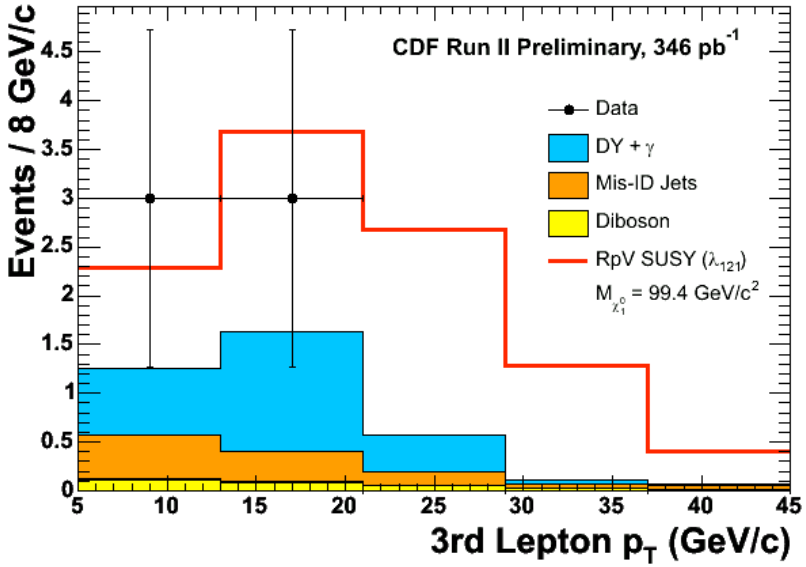
- Search for R-parity violating decay of LSP to leptons:
  - λ_{121}, λ_{122}
  - No bounds from proton decay
  - Enables neutrino oscillations
- Specifically:
  - Decay of lightest neutralino into leptons
  - Can happen in any SUSY process

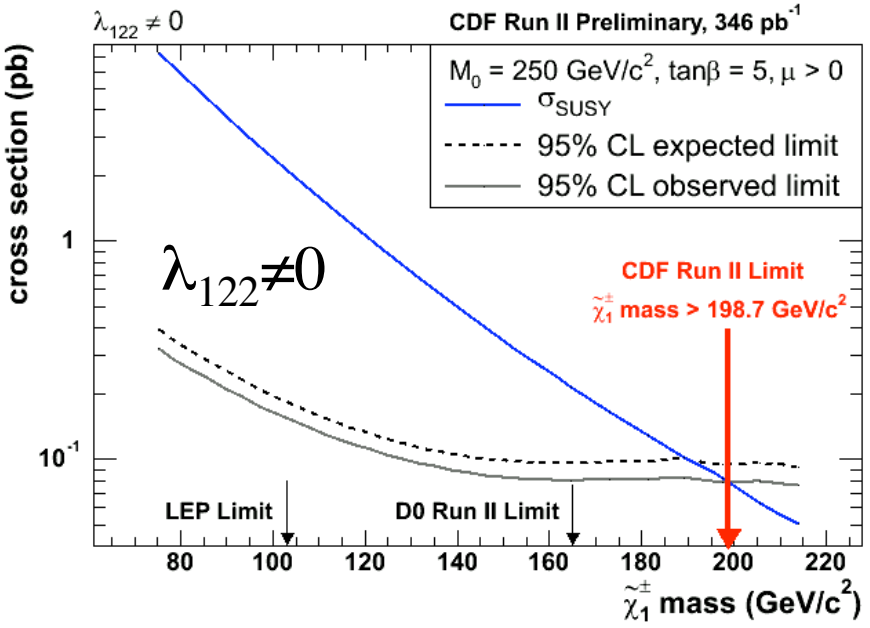
- Coupling strong:
  - Prompt decay: $\tau \approx 0$
- Coupling weak:
  - Lifetime large: $\tau > 0$
- Coupling very weak:
  - Lifetime large: $\tau \gg 0$ => decay products not observed in detectors

RPV: 4 prompt leptons



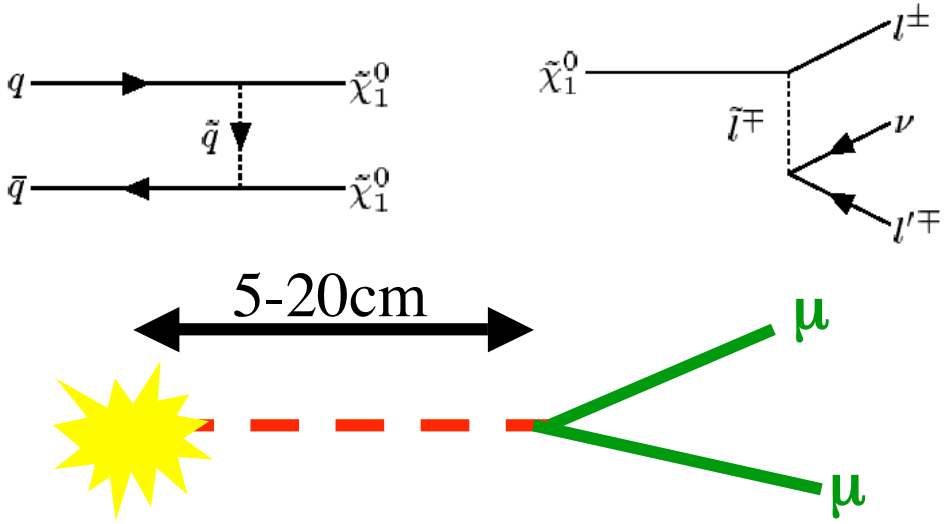
- 2 Neutralinos decay to 2 leptons each:
  - Final state contains 4 prompt leptons
- Result:
  - 4 leptons: 0 events
  - 3 leptons: 6 events
- Constrain SUSY:
  - $M(\chi^{\pm}_1)>198.7$ GeV
  - $M(\chi^{0}_1)>108.4$ GeV

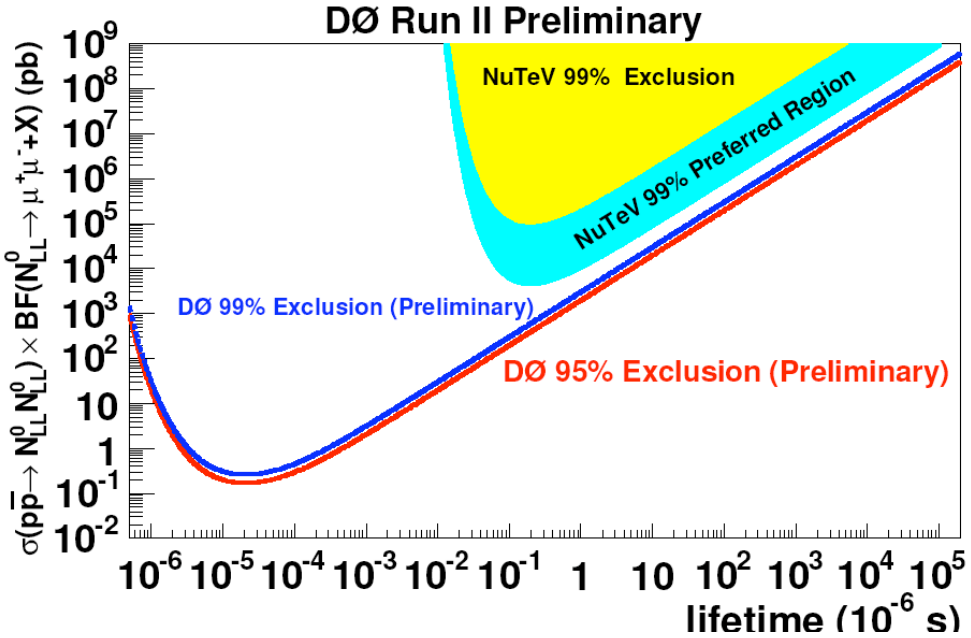




RPV: Longlived Neutralino

- Lifetime of neutralino could be large:
  - Several ns or even μs
  - NuTeV Dimuon excess:
    - 3 events observed
    - 0.069+-0.010 expected
- DØ searched for displaced dimuon pairs
  - 0 events observed
  - 0.75 expected
- More sensitive than NuTeV for this interpretation





Indirect Searches

Rare Decay: $B_s \to \mu^+\mu^-$

- SM rate heavily suppressed:

$$BR(B_s \to \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

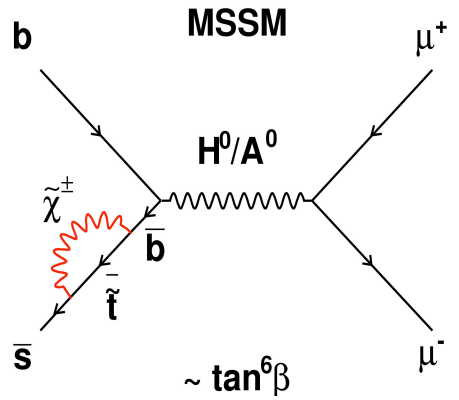
(Buchalla & Buras, Misiak & Urban)

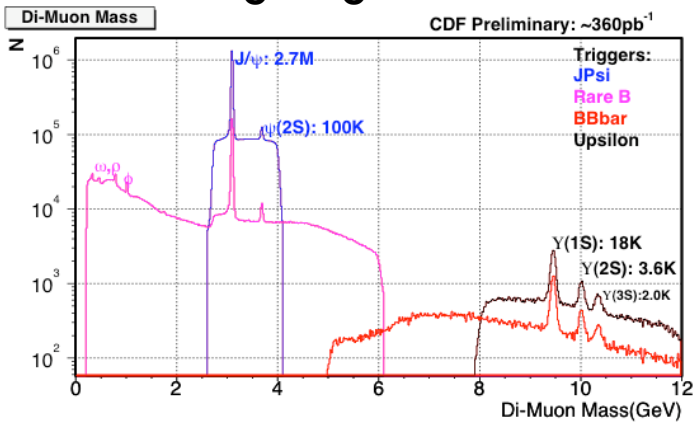
- SUSY rate may be enhanced:

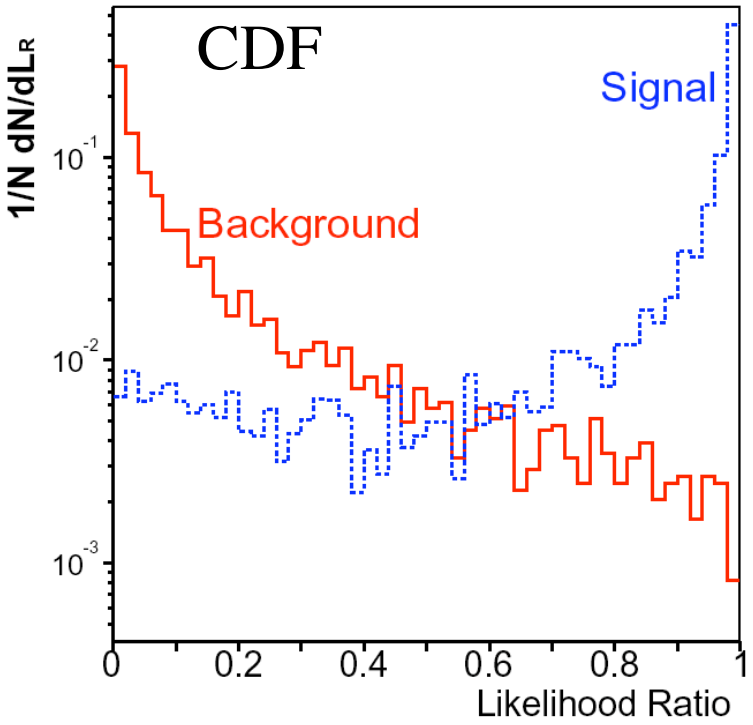
$$BR(B_s \to \mu^+\mu^-) \propto \tan^6 \beta / m_A^4$$

(Babu, Kolda: hep-ph/9909476+ many more)

- Separate from huge background using likelihood ratio:
  - decay length
  - B-meson isolation
  - Pointing angle

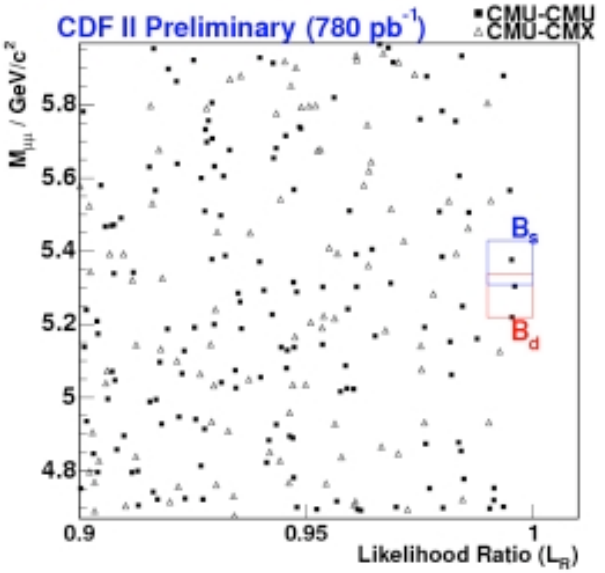




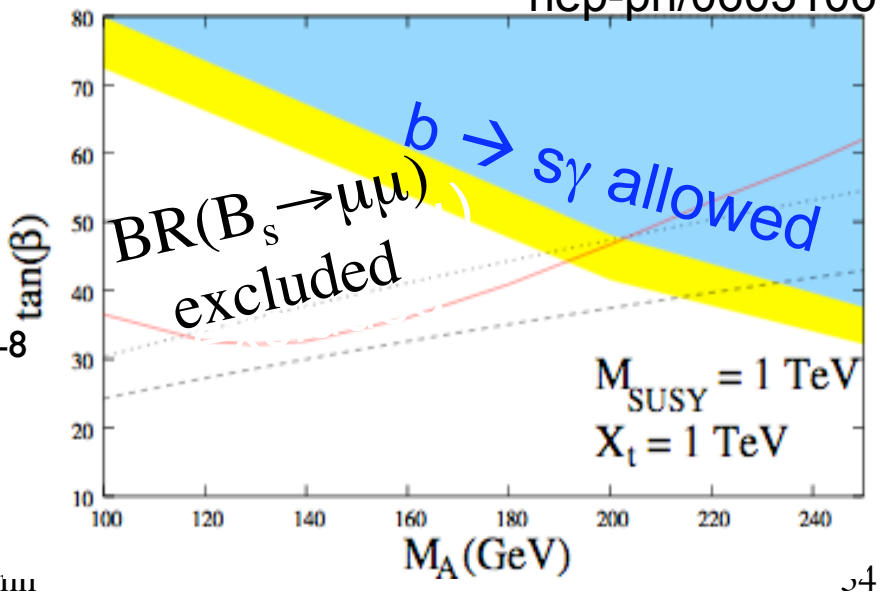


$B_s \to \mu\mu$: Result and Future

- Result:
  - 1 event observed
  - Backgrounds:
    - 0.88±0.30 for (CMU-CMU)
    - 0.39±0.21 for (CMU-CMX)
- Branching Ratio Limits:
  - CDF (780 pb^{-1}):
    - BR($B_s \to \mu\mu$)<10 x 10^{-8} at 95%C.L.
  - DØ (300 pb^{-1}):
    - BR($B_s \to \mu\mu$)<37 x 10^{-8} at 95%C.L.
    - Expect: BR<23 x 10^{-8} with 0.7 fb^{-1}
- Future:
  - Tevatron will probe values of 2x10^{-8}
  - LHC will probe SM with 300 fb^{-1}



hep-ph/0603106



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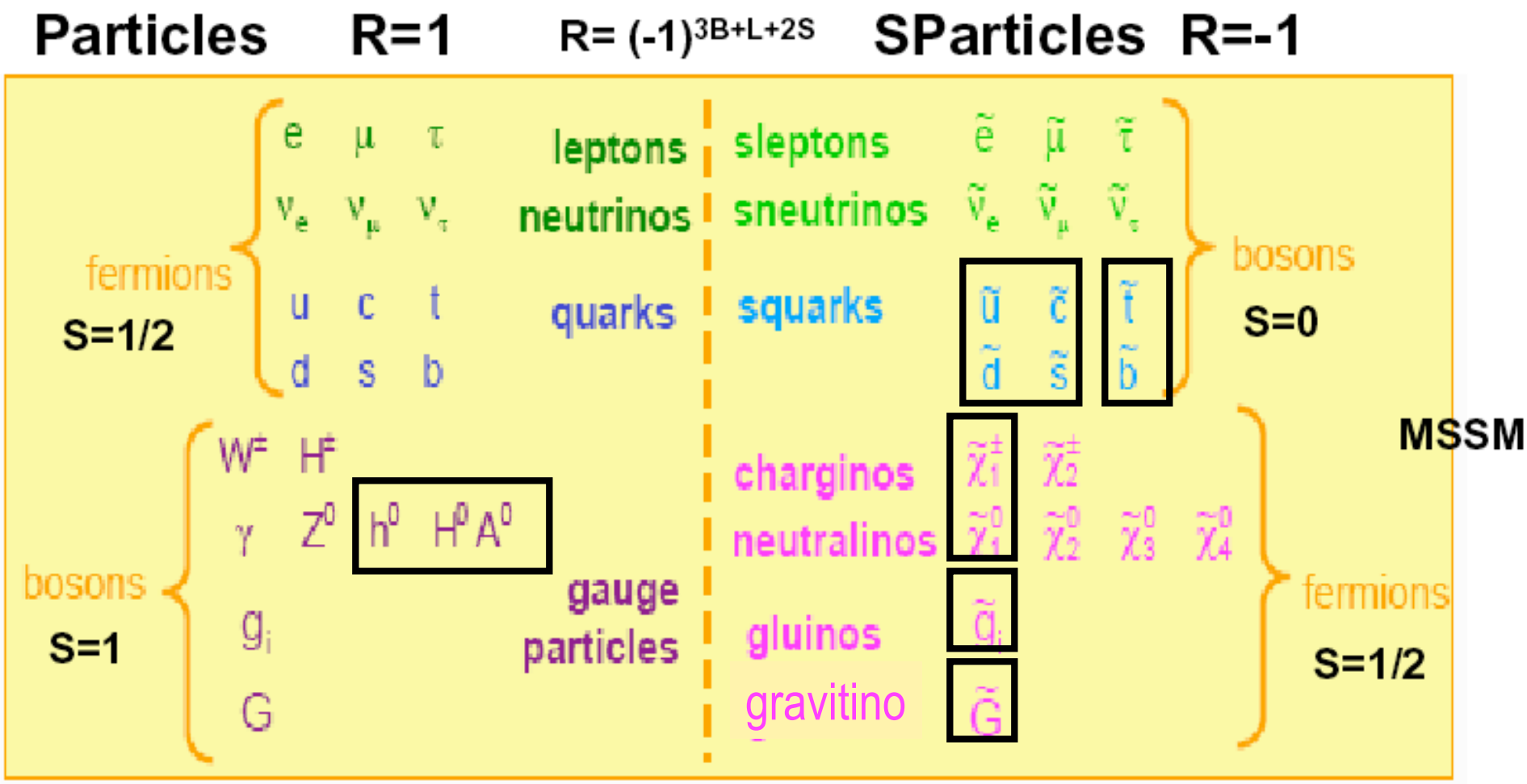
If Nature is supersymmetric we will have a lot of fun, measuring many particles and parameters to find out how it works in detail!

Backup Slides

SUSY Particles



MSSM has 124 parameters:

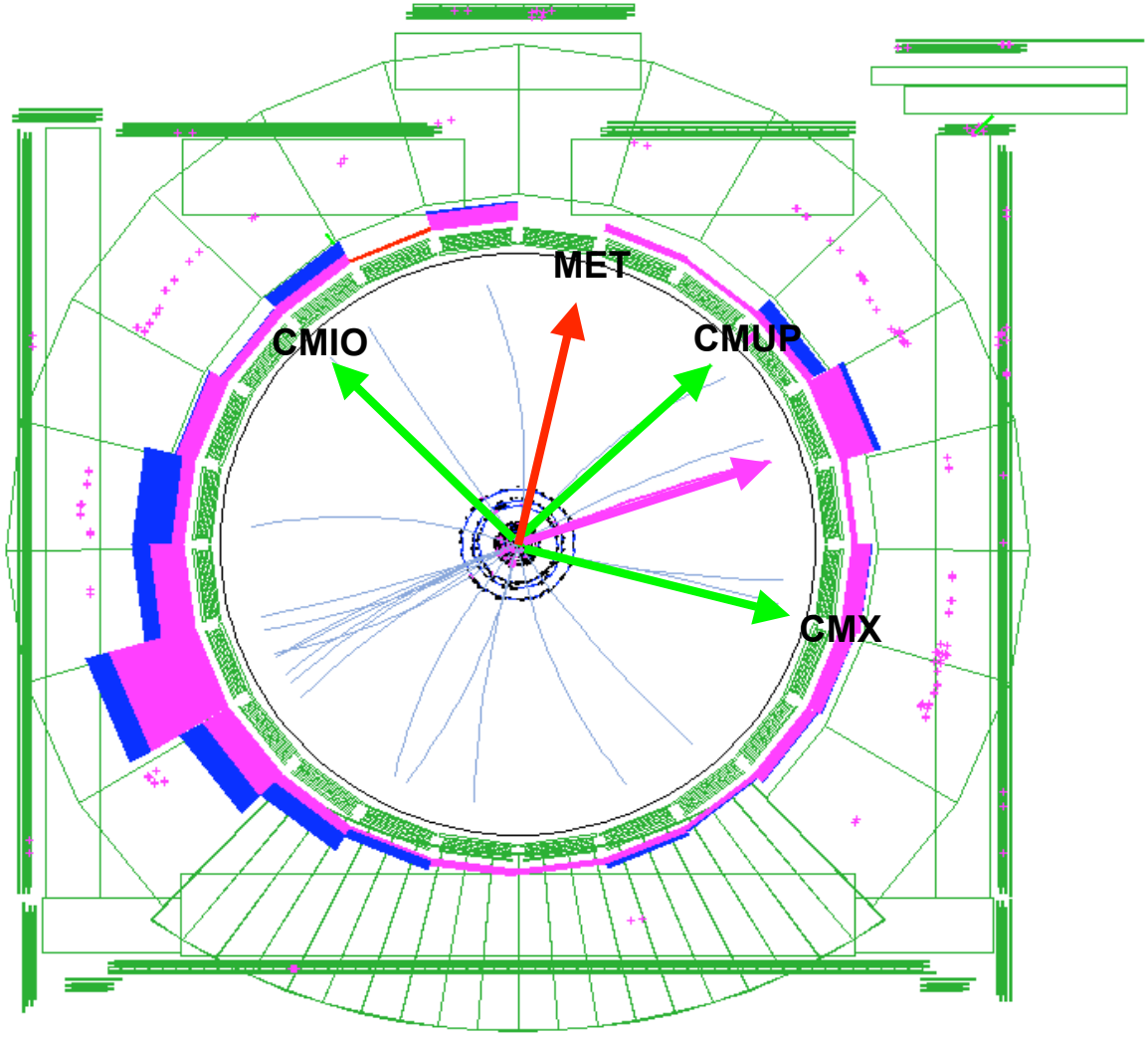
M_1, M_2, M_3, Gaugino masses, Sfermion masses

$\tan\beta$, μ, m_A Higgs(ino) mass/mixing

A_τ, A_b, A_t (+45 RPV)

- **SUSY is a broken symmetry**

A Trilepton Candidate Event

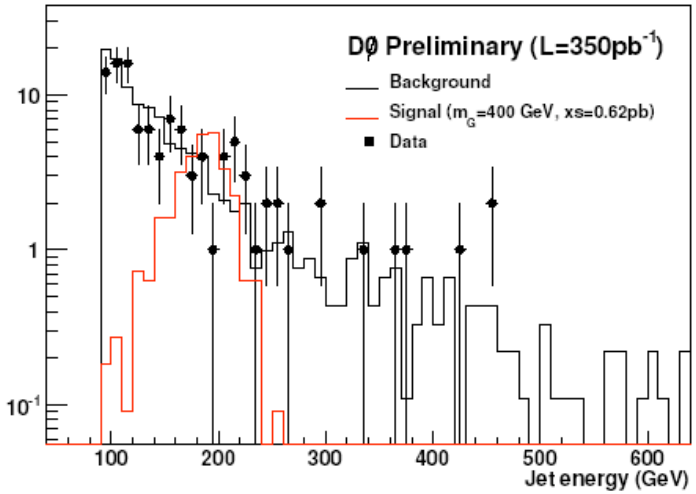


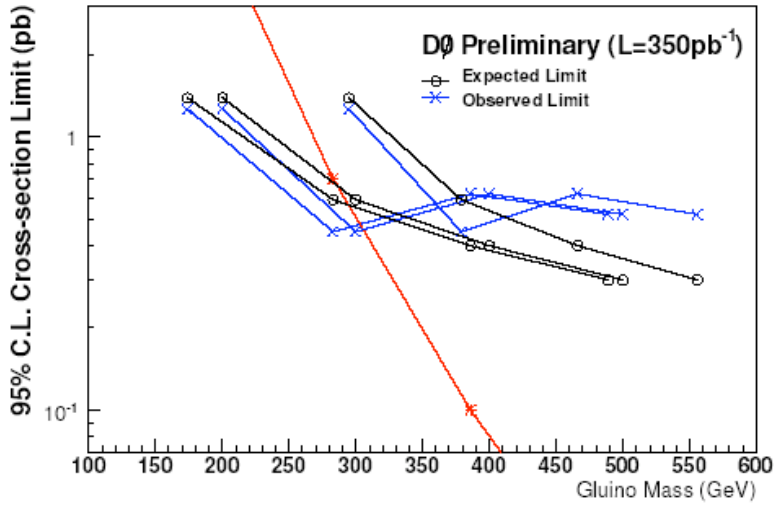
R–parity: to violate or not to violate

- SUSY can violate or conserve R-parity:
  - R=(-1)$^{2S+3B+L}$
  - R conserved:
    - Sparticles produced in pairs
    - Lightest neutralino stable =>candidate for cold dark matter
    - Key signature: missing transverse energy
  - R not conserved:
    - Sparticles can be produced singly or in pairs
    - No missing ET guaranteed
      - Full mass reconstruction possible
    - Could provide mechanism for neutrino mixing
    - Important parameter is the coupling $\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}$
    - Typically allow just one coupling to be large
    - Avoid proton decay (focus on lepton couplings)

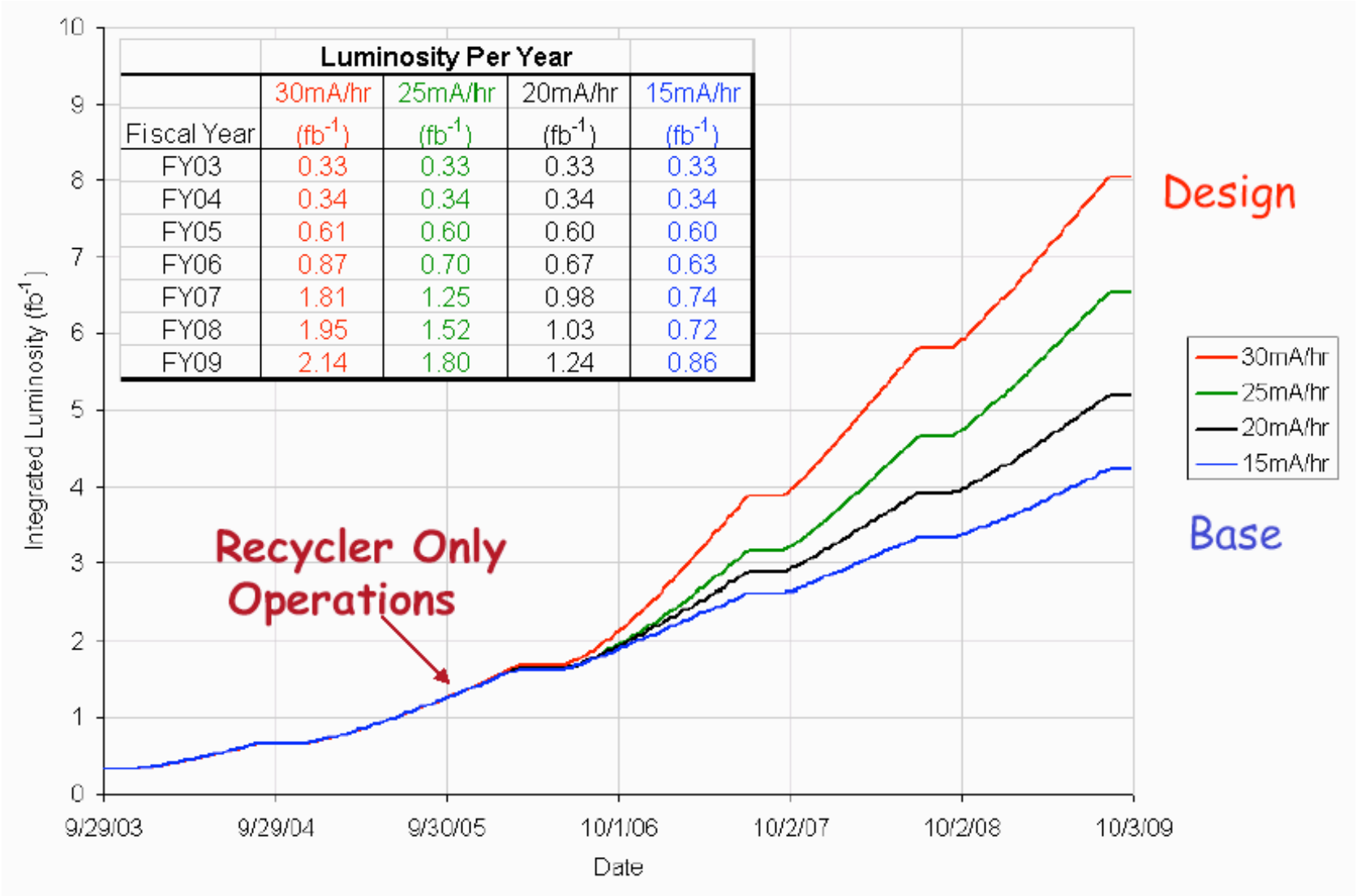
$$W_{\not R_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

Stopped Gluinos



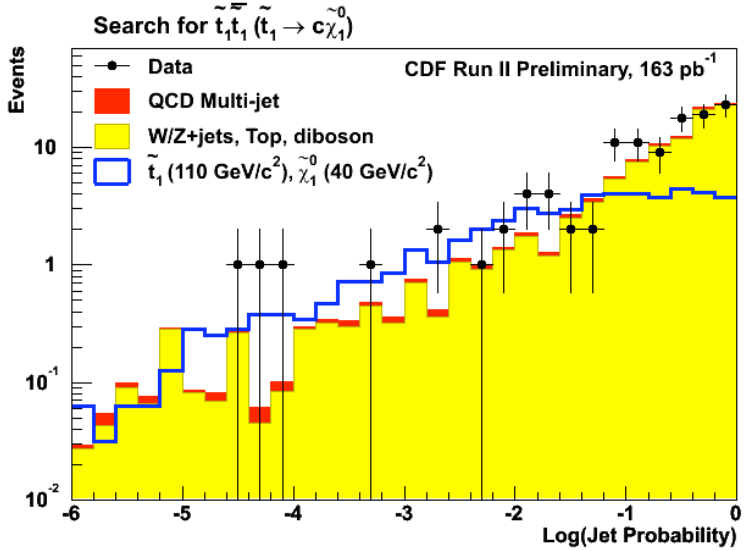


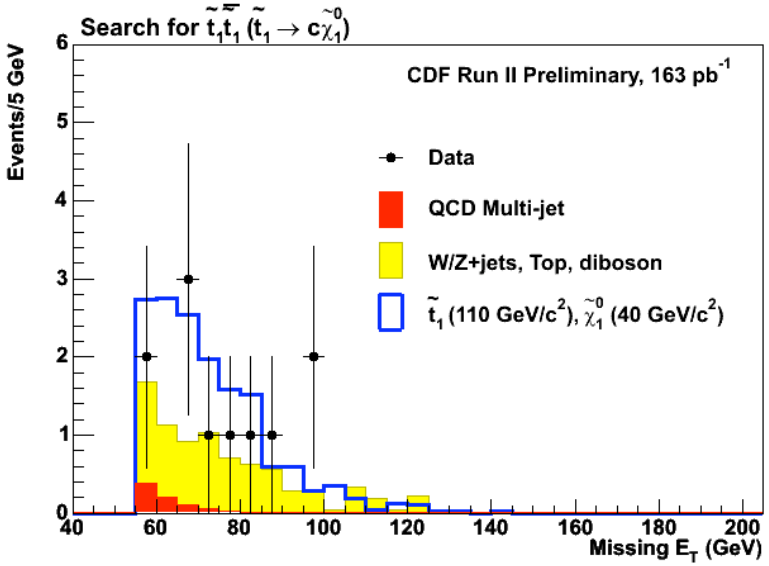
Tevatron: Future



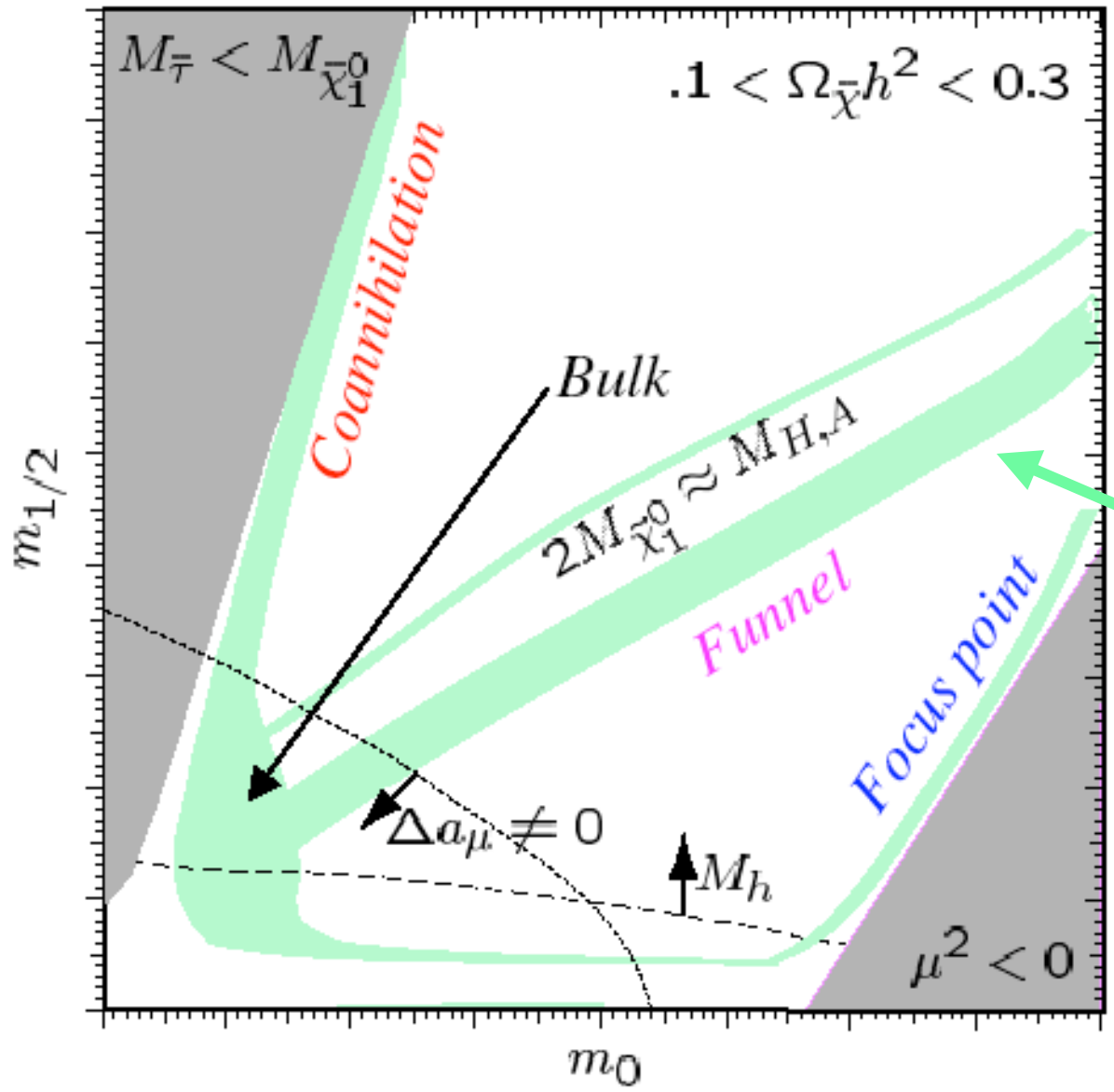
Light Stop–Quark: Result

- Charm jets:
  - Use "jet probability" to tag charm:
    - Probability of tracks originating from primary vertex
  - Improves signal to background ratio:
    - Signal Efficiency: 30%
    - Background rejection: 92%
- Data consistent with background estimate
  - Observed: 11
  - Expected: $8.3^{+2.3}_{-1.7}$
- Main background:
  - Z+ jj -> ννjj
  - W+jj -> τνjj





SUSY and Cosmology Data



Consistent with cosmology data on dark matter

Stop Quark: Result and Future

- Due to slight excess in data:
  - No limit set on stop quark mass yet
- Future light stop reach :
  - L=1 fb^{-1}: m($\tilde{t}$)<160 GeV/c^2
  - L=4 fb^{-1}: m($\tilde{t}$)<180 GeV/c^2
- LHC:
  - Direct production will be tough to trigger
  - But gluino decay to stop and top yields striking signature!
    - Two W's, two b-quarks, two c-quarks and missing E_T
    - If m($\tilde{g}$)>m(t)+m($\tilde{t}$)